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Energy Analysis of UK Industry System with Emphasis on the Iron and Steel Sector

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ENERGY ANALYSIS OF UK INDUSTRY SYSTEM WITH EMPHASIS ON THE IRON AND STEEL SECTOR

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Signed Declaration

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Abstract

This study has focused on the relationship between fossil energy consumption and carbon emission reduction in industry. Energy analysis and exergy analysis based on the First and Second Laws of the Thermodynamics were the main methods for the analysis of the energy saving potential. This is an important commercial way for reduce carbon emission in the sector. After reviewing the current status of energy consumption in UK and its industrial sector, energy use and carbon emissions in UK power generation industry has been briefly analyzed. Finally, the traditional energy-intensive industry, the iron and steel sector was examined. Here energy demand and carbon emissions in each of the main working stages were studied. State-of-the-art energy saving technologies and a low carbon emission iron and steel making methods identified.

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It is a pleasure to thank those who made this thesis possible. Firstly I'd appreciate my parents' finical support. Secondly I would like to appreciate my wife, Yan Shi who gave me continuously strong support in the last 5years and my supervisor, Professor Greoffrey Hammond who helped me with the research material useful direction. Finally, I also would like to appreciate Mr. Craig I Jones who gave me lots of useful experience about research work.

Lei Wang

Content

1. Introduction

1.1 The background of this thesis

After the industrial revolution, coal became the main energy resource for most industries. From the beginning of the 20^{th} century, oil took the place of coal and became the first energy input of the world with the development of internal combustion technology. Even though, coal is still the main primary energy resource serving for most industries, especially electricity industry, iron and steel industry, and most of oil is used as fuel of transport. However, both coal and oil are fossil fuels and the main content in the combustion exhaust gas is CO_2, a kind of greenhouse gas (GHG). GHG in the atmosphere due to the industrialization causes global climate change. The climate change would bring inestimable loss, due to strong storms, floods, and glacier thaws. How to ensure a sustainable development has become a serious global problem that every government has to face. Considering the relationship between energy consumption and exhaust emissions, reducing the energy demand, is an effective way to reach the target of carbon emission reduction.

In order to control GHGs to atmosphere and protect atmospheric circulation from being seriously disrupted, the United Nations concluded the "United Nations Framework Convention on Climate Change" (UNFCCC) in 1992. This Convention requires all countries, especially industrialized ones, to take actions to deal with the global climate change and its prejudicial influence. The UNFCCC requires that industrialized countries should reduce GHGs down to the level before 1990. In December 1997, the contracting parties of the Convention signed the "KYOTO PROTOCOL TO THE UNITED NATIONS FRAMEWORK CONVENTION ON CLIMATE CHANGE". The Kyoto Protocol requires that industrialized countries to reduce GHG emissions 5.2%, against a base of 1990, between 2008 and 2012.

According to the Kyoto Protocol, the Europe Union should reduce GHGs by 8% compared to the emission level in 1990 by 2012. The GHG reduction target allocated to the UK government is

12.5% by 2012. In response to this, the UK govenment made its emission reduction target to reduce carbon emissions by 34% in 2010 on 1990 level (the so-called ‘domestic’ target) [76]. Moreover, according to the Clime Change Act mading in 2008, the long term target is to reduce carbon emissions by 80% by 2050 on 1990 level [76].

On the one hand, as the base of society and economy, industrial sectors play important roles in industrialized countries, supplying not only all articles for people’s life and all human activities but also providing a large number of job opportunities. Industrialization enables society to progress, improves life quality, and creates more economic growth. On the other hand, industry consume billions tones of coal, oil and other raw materials, and emit millions tones of GHGs. Almost all of the extra cumulative CO_2 in atmosphere comes from G8 states following industrialization. Due to high energy intensity and high carbon emissions, optimizing energy use during industrial working processes, and developing low carbon and renewable energy resources or technologies, especially for some energy-intensive industries, are important ways to save energy and control carbon emissions.

The United Kingdom was the first industrialized country; and has evolved plenty of experience in solving the technical problems emanating from its industrial sectors. Researching the industrial sectors in the UK cannot only help identify UK carbon emission reductions, but also contribute useful experience to help other industrialized and emerging economics to reduce the energy consumed in their industrial sectors.

1.2 Aims and Objectives

The aim of this project is to analysis the use of energy in the UK industrial sectors in terms of the Standard Industrial Classification (SIC). Both the quantity of energy use and its quality (or ‘exergy’ degradation) has been examined. The latter involves estimating electricity use and the operating temperatures of fossil-fuelled processes. The cascading of energy in the industrial sectors was then studied to evaluate its energy saving (and carbon mitigation) potential. In order to determine the primary energy inputs needed to produce a given amount of product or service, it is necessary to trace the flow of energy through the relevant industrial subsystem. This idea is based on the First Law of Thermodynamics, that is the principle of conservation of energy, or the notion of an energy balance applied to the system. It leads to the technique of First Law or 'energy' analysis, which is performed over the entire life cycle (or full fuel cycle) of the product or activity from 'cradle to grave'. The technique has been widely used since the late 1970s by academics and UK government departments and agencies, including the former Energy Technology Support Unit at Harwell. It enables energy or heat losses to be estimated, but yields only limited information about the optimal conversion of energy. In contrast, the Second Law of Thermodynamics indicates that, whereas work input a system can be fully converted to heat and internal energy (via dissipative processes), not all the heat input can be converted into useful work. The Second Law therefore suggests the need for the definition of parameters that facilitate the assessment of the maximum amount of work achievable in a given system with different energy sources. This leads (with the First Law) to a roperty is known as 'exergy' that is lost or degraded in every irreversible process or system. In this sense, exergy represents the thermodynamic 'quality' of an energy carrier and that of the waste heat or energy lost in the reject stream. It provides a basis for defining exergy efficiency, and can identify exergetic 'improvement potential' within systems (Hammond, [69])

The present study has utilized mainly thermodynamic (energy and exergy) appraisal techniques in order to determine the relative merits of various industrial energy saving measures. A top-down approach has provided an overview of energy use and exergy degradation in the UK industrial sector. 'Industry' was disaggregated in terms of the Standard Industrial Classification (SIC), and mapped against those industries with trade associations and DEFRA negotiated umbrella agreements for climate change mitigation purposes. SIC have 17 major divisions, along with many sub-classes. In order to analyze energy usage and its effectiveness within the UK industrial sectors, Hammond & Stapleton [2001] subdivided the multitude of processes into four broad categories: low temperature ($T_p<394K$), medium temperature ($T_p=394-692K$),high temperature ($T_p>692K$), and mechanical drives. Although energy analysis enables the determination of a quantitative energy balance across an engineering system, 'exergy' analysis is required in order to ascertain the ways in which the energy flows are qualitatively degraded. The scope for thermodynamic improvement potential was evaluated on a disaggregated basis; perhaps using something like the 45 sub-sectors adopted for DEFRA negotiated Climate Change Agreements. The energy balance for the industrial sector will be established initially, whist the exergy budget was determined at a later stage of the project. That enabled the scope for the optimal use of primary energy inputs into industry to be ascertained. The thermodynamic performance of the British iron and steel industry was examined in the first instance as a means to determining the feasibility of the overall approach.

1.3 Structure of the thesis

This thesis firstly introduces the concept of sustainable development, and then gives a general background to energy use in the British industrial system. The energy system is divided into energy supply side and end-user side, for convenience of analysis. Power generation industry is a special industry because it consumes a large amount of primary energy and supplies a high quality energy carrier, electricity. Since electricity is widely used by today's society, including industry, a literature review and analyzing of the UK power generation industry was initially undertaken this identified the energy saving potential in power generation and utilization. It also sorts to identify carbon emission reduction potential bought by low carbon energy technologies.

On the energy end-user side, industrial sectors have become the second large of energy consumer in today's UK. Industry is generally a high energy-intensive end-user, unlike the domestic sector. Energy consumption in industrial sector often has specific chrematistics, such as high temperature, and high driving force. Using different types of energy directly can avoid the energy loss in the energy transformation among different energy forms.

The iron and steel industry is a traditional energy-intensive industry. It requires high temperature for iron ore reduction and high temperature for the crude steel production and steel rolling. Coke is the main energy supplier and reduction agent of the iron industry, so the iron industry is also a large emitter of GHGs. It is very useful to find effective ways to reduce energy use and GHGs in the iron and steel industry which could contribute to carbon emission reduction. The UK is relatively advanced in the industrial field, and the research of energy consumption and carbon emission reduction in UK iron and steel industry can therefore yield useful experience for the global iron and steel industry.

2. The relationship between energy consumption and sustainable development

2.1 Introduction

The GHGs in atmosphere as a result of human activities after industrialization have a potentially serious environmental impact due to global warming. These include glacier melting, flooding, and storms. Such negative impacts may cause sea level rise, cultivated land reduction, some area in drought, and food shortage. These disasters threaten people's living directly. However, fossil fuel resources, like petroleum and coal, are non–renewable resources and have acted as the main primary energy input for over two hundred years for the countries of the industrialized North. It is difficult to support the increasing energy demand with limited fossil fuels. In order to protect our environment without degrading the quality of life, sustainable development has become a new concept guiding human activities. As the major resource and the base of the society, energy use affects all aspects of the society. During the processes of energy obtaining from fossil fuel, CO_2, SO_2, NO_x and other exhaust emission pollute the atmosphere day by day and destroy the environment. The relationship between fossil fuel consumption and GHGs are discussed in this chapter in the context of the UK carbon emissions, and the need to secure sustainable development.

2.2 Energy consumption in the UK

Energy is a critical and essential resource in modern society, especially in the industrialized countries. The industrialized economics require energy utilization technology and improvements in converting efficiency, which are both brought about achievements in sciences and technology. From the Steam Age to the current Electric Age, the exploitation of different energy resources and the methods to utilize energy resources characterized the technical progress of society. As the first industrialized country, the United Kingdom witnesses many technical innovations after the industrial revolution. Therefore, industrial development and related changes in energy utilization is associated with the history the industrial society in the UK. In the 1700s, 'heat engines' were invented, and they became the main drivers of ships and trains. Coal, as the fuel for steam boilers and the raw material of coke production for iron and steel industry, was exploited in quantity and drove the UK's economy. At the end of the 19^{th} century, with the invention of internal combustion engine, the demand for oil increased dramatically. Breakthroughs in electrical engineering also made it possible for electricity to go into the energy system as the main power supplier. Electricity is a high-grade energy carrier in the sense that it can be used to provide either power or heat (Hammond, 2001 [1]) easily and efficiently; therefore, it soon became a principle choice for many energy end-users. Electric motors then took the place of steam turbines to drive machines in many factories. A large number of power plants were established and supplied electricity to all customers through an electricity grid. The Electric Age took the place of the Steam Age. After the Second World War, new techniques flooded into society and changed people's lives. Many of energy resources are new utilized for power generation attributing to the application of new techniques, including nuclear power. The nuclear power generation industry has played a significant part in the energy system of many industrialized countries.

In the UK, energy consumption influences most economic activities, from workshop to kitchen, everywhere energy is necessary. Energy supply has become the basis for human development, not only for economic growth, but also for raising people's quality of life. The UK energy system structure is depicted schematically below (see Figure 1):

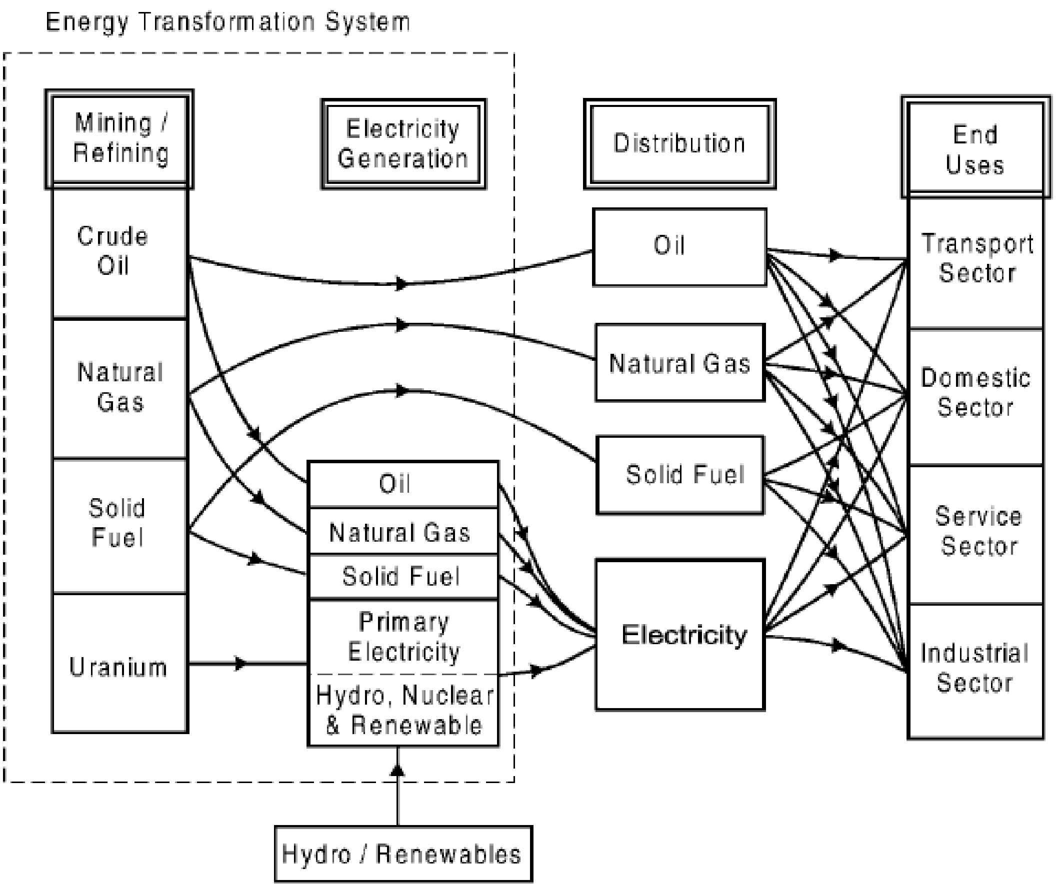


Figure1: Simplified representation of the UK energy system. (Source: Hammond [2])

Here end-users are grouped into four main sectors:, transport, domestic, service and industrial. It is also indicated in Figure 1 that the primary energy consumption in the UK consists of crude oil, natural gas, solid fuel (coal in the main) and primary electricity (generated by nuclear power, hydraulic power and renewable energy resource). Although the primary energy resources in the UK are various and the proportion of non-fossil fuel energy consumption has increased dramatically in the past four decades, fossil fuels have still dominated most of the energy market in the past three decades (See Table 1& Figures 2 and 3).

Type of Primary Fuel		1970 (%)		2010 (%)	
Fossil fuels	Coal	47.1	96.5	14.8	89.8
	Petroleum	44.0		32.3	
	Natural Gas	5.4		42.7	
Nuclear electricity		3.3		6.4	
Hydro-electricity		0.2		0.5	
Net electricity imports		0		0.1	
Renewables & waste		0		3.2	

Table 1: Percentage shares (energy supplied basis). (Source: DECC 2011, [77])

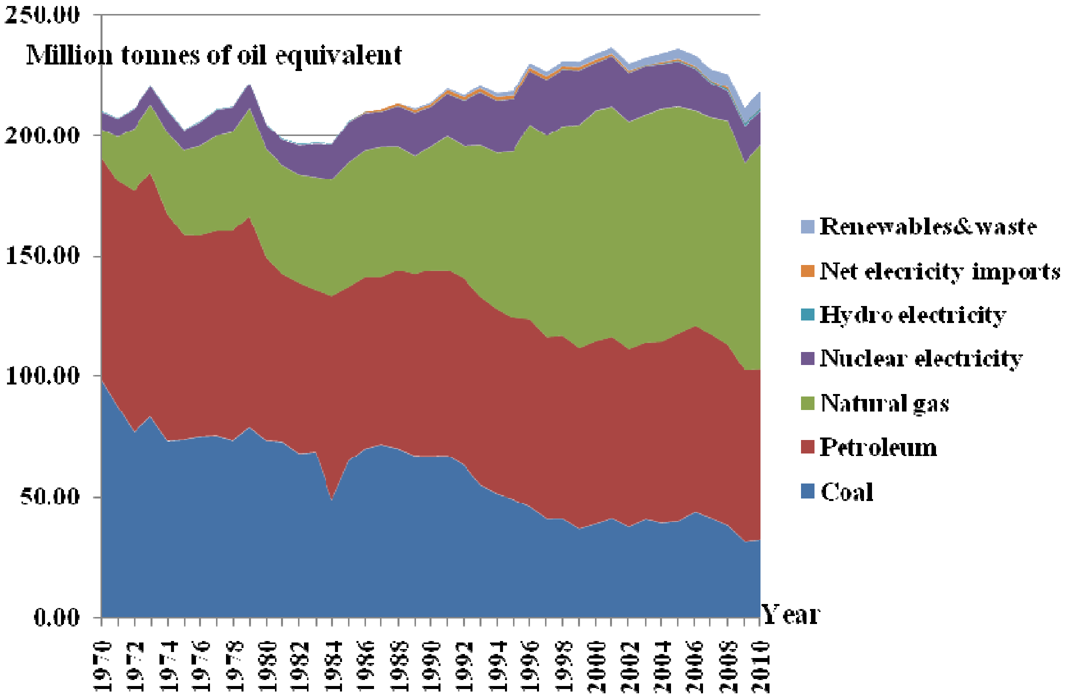


Figure2: Inland consumption of primary fuels for energy use, 1970 to 2010. (Source: DECC 2011, [77])

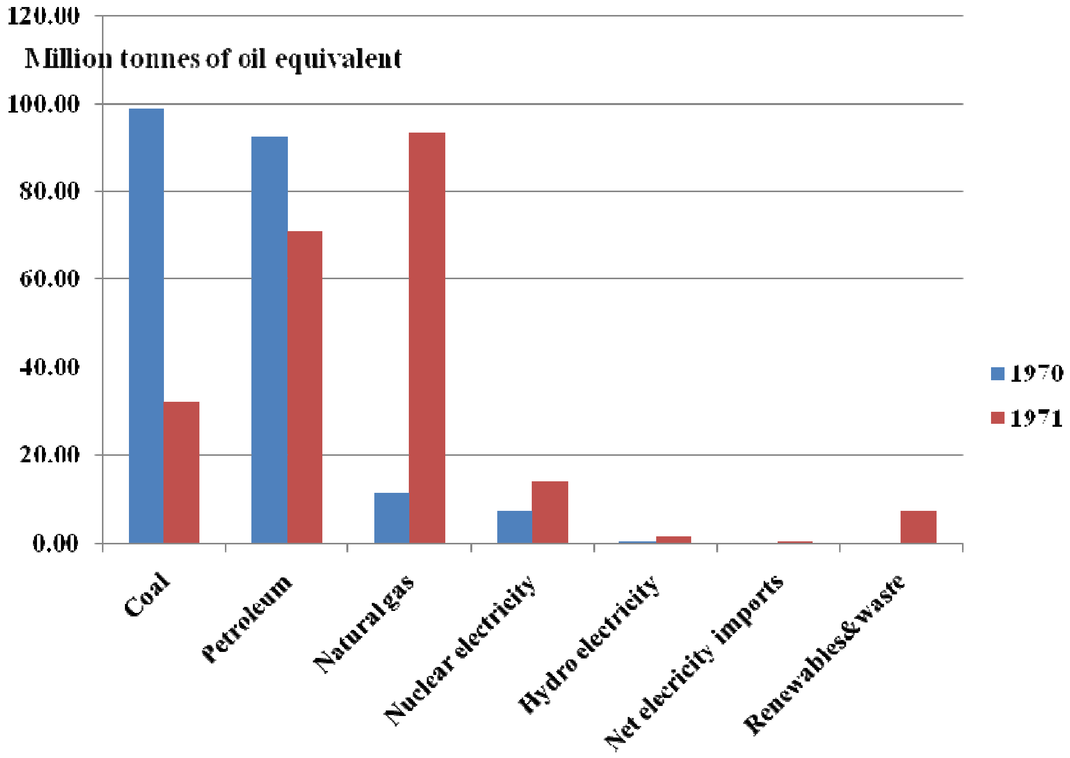


Figure3: Primary energy consumption in 1970 and 2004. (Source: DECC 2011, [77])

From 1970 to 2010, the total inland consumption of primary energy increases 8.4 million tonnes of oil equivalent (see Table 2). Most of the increase comes from the use of nature gas (see Figures 2 & 3). The consumption of natural gas in 2006 was as 8.25 times as the level in 1970 **(Source: DECC 2011, [77]).** One the contrary, the consumption of coal decreases by 67% and the consumption of petroleum decreased by 23% since 1970 **(Source: DECC 2011, [77]).**

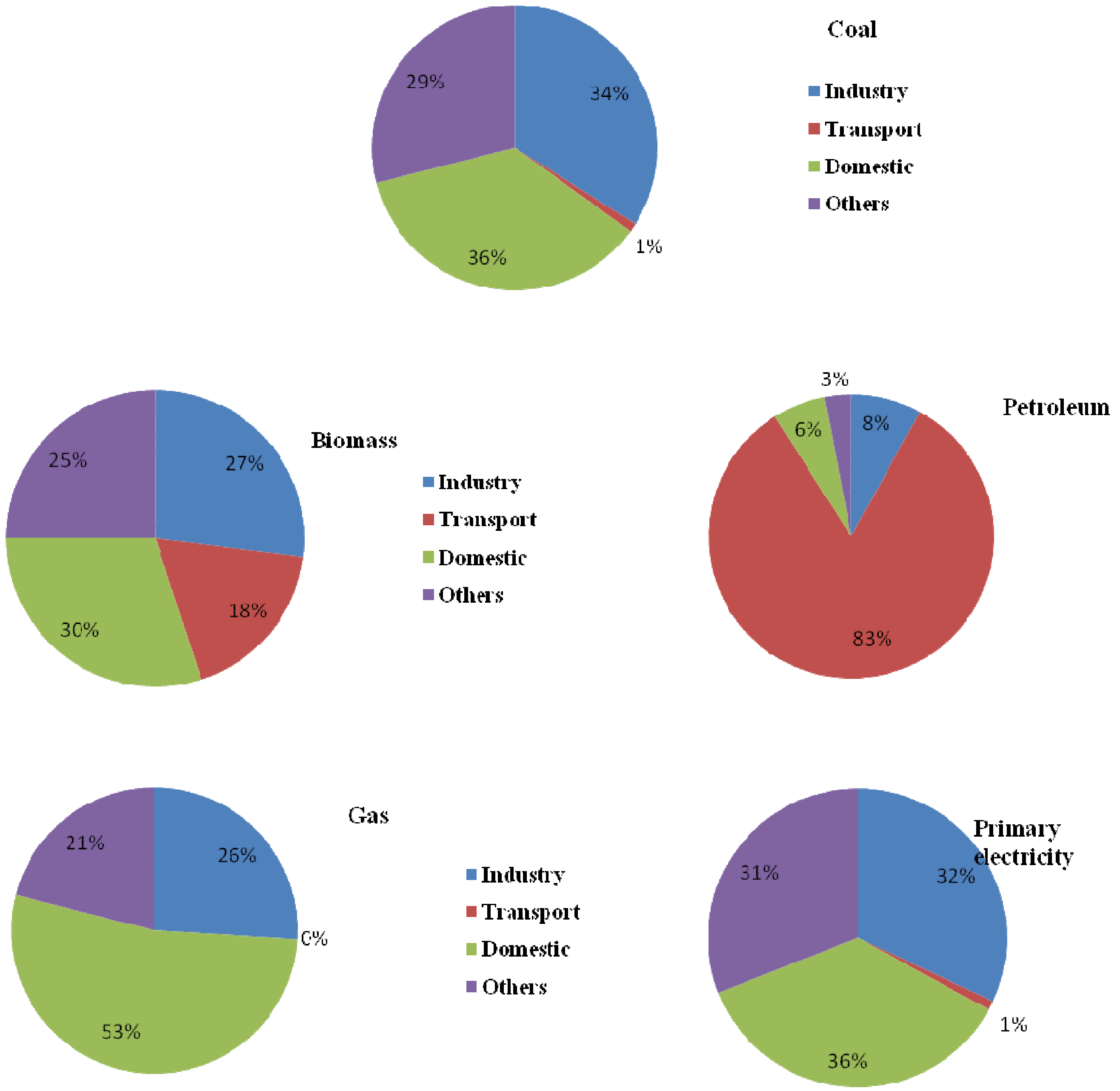


Figure 4: Percentages of each primary fuel consumption by final users in 2010. (Source: DECC 2011, [77])

Not only has the quantity of consumed energy changed over recent decades, but the energy consumption structure has changed as well. Due to the wide use of gas-fired central heating system in families, natural gas has taken the place of coal to become the main energy resource for space heating in winter, cooking and hot water supply for families. Thus, the domestic sector has become the largest natural gas consumer in UK (see Figure 4). Moreover, the largest single consumer of energy in 2010 was transport sector, accounting to 37 percent. In1970 the largest one was industry at 43% (see Figure 6). The reason why the largest consumer switched is some of energy-intensive industries have been moved abroad [3]. According to analysis from the end-user side, space heating and hot water accounted for 82 percent of domestic use of energy and 64 percent of commercial use of energy in 2000 [3].

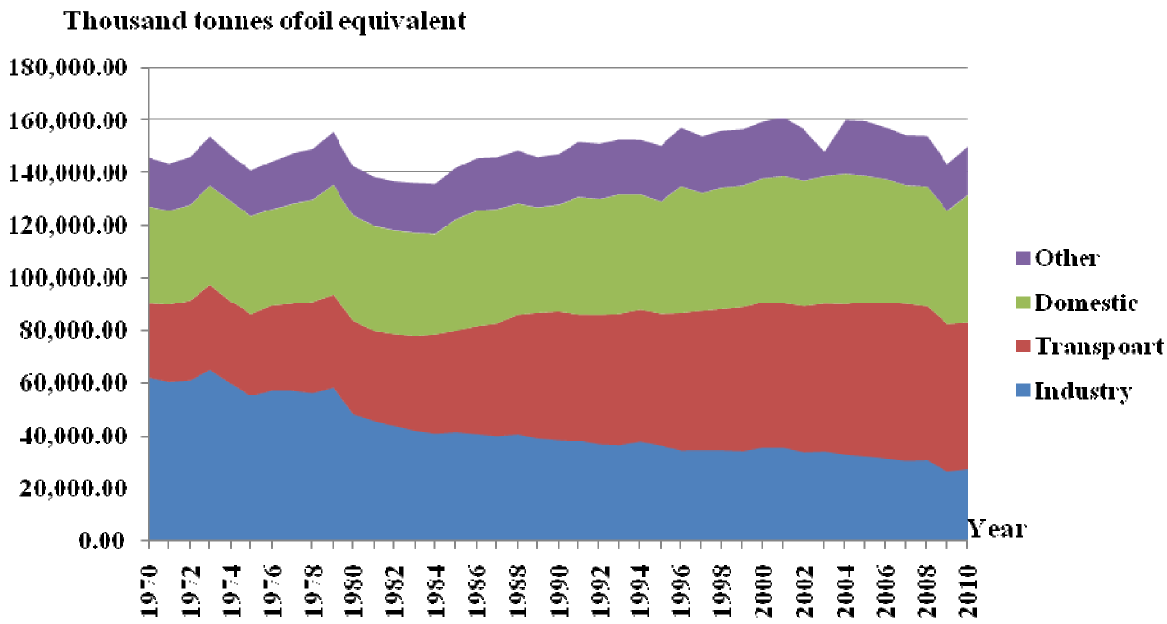


Figure.5: Energy consumption by final user, 1970 to 2010. (Source: DECC 2011, [77])

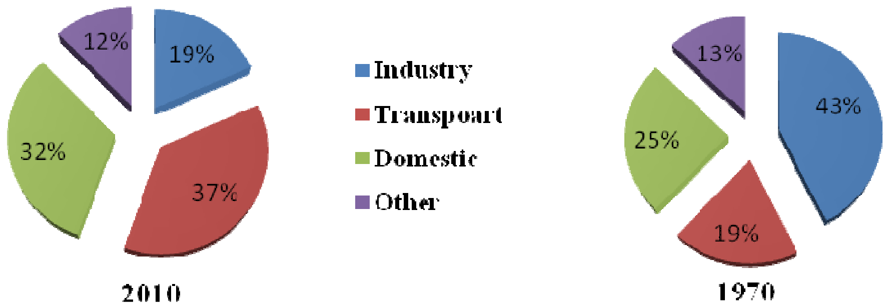


Figure.6: Percentage sector shares in total energy consumption, 1970 and 2010. (Source: DECC 2011, [77])

2.3 Relationship between energy consumption and CO_2 emission

As has been discussed in last chapter, CO_2 account for a proportion of all GHGs and most of the atmospheric carbon emissions were emitted post-industrialization, due to the combustion of fossil fuels. When the energy system in industrialized countries is examined from the end-user side, it can be seen that energy demand may be divided into two categories, one is electricity use, and the other is non-electricity use. Electricity, a secondary energy carrier is widely used for all kinds of energy end-uses. The non-electricity consumption is that which utilizes fossil or hydrocarbon fuel, such as coal, petroleum and natural gas, for heating and transport (burning largely in IC engines). Electricity from thermal power plants (which is termed secondary electricity in order to distinguish it from primary electricity, such as hydroelectric power, wind power and solar power), takes a large share of power supply. Nuclear power plants are also a type of thermal power plant, but because there is no other way to utilize the nuclear power directly, electricity from these plants can be seen as a kind of low carbon primary electricity. In fossil fuelled power plants, from conventional coal-fired power plant to combined cycle gas turbine (CCGT) power plant, the generation of electricity all depends on the burning of hydrocarbon fuels. During this process, CO_2 and water are the main by-products. The quantity of carbon emitted from hydrocarbon fuel combustion is decided by the type of fuel, as well as the amount of fuel consumed.

In order to determine accurately the amount of carbon emitted from fossil fuel combustion, the methodological tool [4] developed by the UNFCCC can be employed. This is applied principally for Cleaning Development Mechanism (abbreviated to 'CDM') projects, but also can be adopted to calculate CO2 emissions from fossil fuel combustion.

2.3.1 Review of UNFCCC (abbreviation of 'United Nations Framework Covention on Climate Change') Methodological Tool to calculate CO_2 emissions from fossil fuel combustion [4]

This tool is based on the quantity of fuel combusted and its properties. Accordingly, CO_2 emissions from fossil fuel combustion in process *j* are calculated based on the quantity of fuels combusted and the CO_2 emission coefficient of those fuels, as follows:

$$PE_{FC,j,y} = \sum_i FC_{i,j,y} \times COEF_{i,y} \qquad (1)$$

Where:
$PE_{FC,j,y}$ are the CO_2 emissions from fossil fuel combustion in process *j* during the year *y* (tCO_2 / yr);
$FC_{i,j,y}$ is the quantity of fuel type *i* combusted in process *j* during the year *y* (mass or volume unit / yr);
$COEF_{i,y}$ is the CO_2 emission coefficient of fuel type *i* in year *y* (tCO_2 / mass or volume unit); *i* are the fuel types combusted in process *j* during the year *y*.

The CO_2 emission coefficient $COEF_{i,y}$ can be calculated following two procedures, depending on the available data on the fossil fuel type *i*, as follows:

Option A: The CO_2 emission coefficient $COEF_{i,y}$ is calculated based on the chemical composition of the fossil fuel type *i*, using the following approach:

If $FC_{i,j,y}$ is measured in a mass unit: $COEF_{i,y} = W_{C,i,y} \times 44/12$ (2)

If $FC_{i,j,y}$ is measured in a volume unit: $COEF_{i,y} = W_{C,i,y} \times \rho_{i,y} \times 44/12$ (3)

Where:
COEFi,y is the CO_2 emission coefficient of fuel type *i* (tCO_2 / mass or volume unit);
$W_{C,i,y}$ is the weighted average mass fraction of carbon in fuel type *i* in year *y*(tC / mass unit of the fuel);

$\rho_{i,y}$ is the weighted average density of fuel type i in year *y* (mass unit / volume unit of the fuel); *i* are the fuel types combusted in process *j* during the year *y*.

Option B: The CO_2 emission coefficient COEFi,y is calculated based on net calorific value (Lower Heating Value in American useage) and the CO_2 emission factor of the fuel type *i*, as follows:

$$COEF_{i,y} = NCV_{i,y} \times EF_{CO2,i,y} \tag{4}$$

Where:
$COEF_{i,y}$ is the CO_2 emission coefficient of fuel type *i* in year *y*(tCO_2 / mass or volume unit);
$NCV_{i,y}$ is the weighted average net calorific value of the fuel type *i* in year *y* (GJ/mass or volume unit);
$EF_{CO2,i,y}$ is the weighted average CO_2 emission factor of fuel type *i* in year *y* (tCO_2/GJ); *i* are the fuel types combusted in process *j* during the year *y*.

The expositor above illustrates the relationship between CO_2 emission and fuel combustion. The quantity of fossil fuel input decides the amount of final CO_2 emission. In order to achieve some target for carbon emission reduction, there are three useful methods that can be used to reduce fossil fuel demand effectively. On the energy input side, the first step is to adopt low carbon or no-carbon energy to replace fossil fuel. On the demand side, energy efficiency measures (such as recovering waste heat during fuel combustion and thermal power utilization processes) can be employed in order to limit fossil fuel consumption. The last step on end-user side is to saving energy by using energy saving technologies to reduce energy demand. The following chapters will discuss the relevant contents about energy saving in two major interrelated energy intensive sectors: the electricity industry and the iron and steel industry in the UK. They are the main coal consumers, and the two biggest CO_2 emitters from British energy system.

2.4 Sustainable development in the UK

2.4.1The concept of sustainable development

There are several types of GHGs in atmosphere (such as CO_2, NO_2, CO, O_3, CFC_s and CH_4) that absorb long-wave radiation, and then warm the Earth. However, the concentration of GHGs in atmosphere has increased dramatically due to industrialization and increasing population size. In the last 200 years, the CO_2 in atmosphere increased 25 percent, NO_2 and N_2O increased 19 per cent, and CH_4 content in atmosphere is as double as 200 years ago. Carbon dioxide accounts for more than four-fifths of greenhouse gas emissions [5]. The data from the IEA shows that carbon dioxide emissions in OECD countries (most of the developed world) increased 16 per cent between 1990 and 2003. For the world, as a whole, the increase was 20 per cent [5].

Due to the industrialization, the over emitted GHGs accumulate in the atmosphere and prevent the reflection of solar radiation back out into the space. Therefore, more heat is kept within the Earth eco-system, thereby increasing the average temperature of the planet. Global warming can cause a series of natural disasters. The increasing Earth temperature makes more glaciers melt and expands the oceans, s that the sea level I likely to rise. Moreover, with the reduction of glaciers and the increase of sea temperature, the normal sea currents and atmosphere cycle would be changed and that would alter the change of global climate. Someplace will be flooded, some will experience drought. Cyclones, storms and high temperature weather in summer will happen frequently. The report of environment impact given by the DTI [5] gives three main aspects of global climate changes to the world and UK:

"**1. The impacts of climate change could, in the longer term, be substantial. Its impacts could include many millions more people exposed to hunger, water stress and flooding. Additionally, low-lying areas, wetlands and small islands will be exposed to risks from rising sea levels, especially in South East Asia. There will be irreversible losses of biodiversity.**

2. Climate change will impact on the UK through changes in the weather: warmer drier summers and milder wetter winters. The changing weather will impact on many aspects of

our lives at home and work. Gardeners and others will find our biodiversity changing, with some species unable to survive in the UK as their habitats change whilst other more exotic ones not native to the UK may thrive.

3. Farmers will find new pests and diseases may affect crops and livestock. The UK tourism industry might benefit from warmer weather but the insurance industry could face bigger payouts for damage caused by storms. There will be many changes, often difficult to see, to which we will need to adapt.”

From 1970 to 2010, primary energy consumption in UK inland increased 0.1 percent per year and average annual Gross Domestic Products (GDP) increase 9.47 percent over the same period (see Table 2). Therefore, the energy ratio dropped from 4064.22 tonnes of oil equivalent per £1 million GDP in 1970 to 149.28 tonnes of oil equivalent per £1 million GDP in 2010. “So there has been a significant reduction in energy use per unit of output. However, it is vital for the future of our planet, that there is further decoupling of the trend of carbon dioxide emissions from increased income and wealth. At the same time, people in many parts of the developing world will be looking to increase their living standards towards the levels that people enjoy in the developed countries [5].” keeping the economy growing without destroying the environment, especially the conflict between increased energy demand and green gas emission reduction, has become a huge challenge that both developed countries and developing countries have to face.

	1970	2010	Increase	
			Absolute growth Value	Average annual growth percentage
Total inland consumption of primary energy (temperature corrected), ***Million tonnes of oil equivalent***	210.1	218.5	8.4	0.10%
Gross domestic product at market prices ***£ million***	51,695	1,463,734	1,412,039	9.47%
Energy ratio ***Tonnes of oil equivalent per £1 million GDP***	4,064.22	149.28	-3,914.95	-7.73%

Table 2: GDP, energy consumption and energy ration changes, between 1970 and 2010. (Source: DECC 2011, [77, 78])

In order to ensure the environmental protection and conserve natural resources with a growing of economy, the concept of 'sustainable development' was first adopted in the 'Brundtland Report' produced by the World Commission on environment and Development (WCED, 1987) [6]. The WCED (1987) defined sustainable development as meeting 'the needs of the present without compromising the ability of future generations to meet their needs'. It therefore involves a strong element of intergenerational ethics [6]. Engineers have generally been slow to meet the challenge of making a reality of the notion of sustainability, although the engineering profession now sees the importance of using their skills to improve the quality of life [6]. The so-called Environmental Pillar of sustainable development necessitates the saving of natural resources and protecting the environment.

Currently, fossil fuels, like coal, petroleum and natural gas, are still the main energy resource in industrialized countries, either for space heating or for electricity generation. Fossil fuels are non-renewable energy resources, so saving energy and improving energy conversion efficiency are effective methods to delay the fossil fuels supply. However, the ultimate way to resolve energy shortage is to find new ‘clean’ renewable energy resources to replace fossil fuels. In fact, the combustion of fossil fuels produces millions of tonnes of carbon dioxide and other waste gases. The processes of burning one tonne standard coal can generate 2.6 tonnes CO_2. As it is discussed above, reducing the utilization of fossil fuels and developing new low or zero carbon energy technologies can decrease carbon emissions effectively. According to the International Energy Agency, 85% of world’s energy demand will be supplied by fossil fuels over the next 25 years. If there are no effective carbon controls, an increase in fossil fuels demand would make carbon emissions grow by 60% [5]. Therefore, efficient use of energy and clean energy technology must be adopted to build a low carbon energy system and meet the requirement of carbon emission reduction.

According to the priciple of ‘sustainable development’, the United Nations Framework Convention on Climate Change was adopted at the Earth Summit in Rio de Janeiro in 1992 and, five years later, it was Kyoto Protocol. This Protocol is an important step that indicates carbon emission reduction actions has been implemented from 2008 and most of the countries in the world have recognised the importance of sustainable development, and the potential harm of global warming. The Kyoto Protocol requires developed countries to ratified it to reduce their carbon emission below 1990s level in between 2008 and 2012, which is the first carbon emission reduction period, and then the secong carbon reduction period would be the next 5 years starting from 2013. The Kyoto Protocol gives each developed country that ratified it a GHG reduction target.

2.4.2 The targets and measurements of sustainable development in the UK

As one of the major developed countries, the United Kingdom has been at the fare front of arguing for climate control and carbon emission reduction. The Kyoto Protocol set the GHG target for EU of an 8% reduction compared with the 1990’s level by 2012. The UK’s Energy White Paper published in March, 2003 gave a much stricter ‘domestic’ target that United Kingdom will reduce 34% carbon emission compared with the 1990’s level in 2010 [76]; it now aims to reduce by 80% carbon emissions by 2050 on 1990 level according to the Clime Change Act made in 2008 .

2.5 Summary

The UK has agreed for GHG control to prevent global warming. However, due to the huge energy demand and the requirements of social development, the pressure of carbon emission reduction is a difficult task. Considering the relationship between energy consumption and carbon emissions, saving energy, especially of fossil fuels, is the direct and effective route to reduce CO_2 emission. In the next chapter, exergy analysis method will be introduced to evaluate this energy saving potential, and it is the employed for the iron and steel industry. Moreover, as the biggest fossil fuel consumer, the electricity industry in the UK will be examined in order to identify fossil fuel saving and carbon reduction from energy use.

3. Application of thermodynamic methods in energy consumption analysis

3.1 Introduction

Thermodynamic methods are useful tools and widely applied to track the energy consumption processes and analyzes the energy input and output in order to determine their energy saving potential, especially in regard to fossil fuels. In today's industrial society, coal, petroleum and natural gas are still the main primary energy input, and most of this is consumed for power generation, space heating, and other combustion processes. From boiler plant to internal combustion engines are dominant. Except solar power, depending on current technology, mechanical power is the only energy generator that can be used to generate electricity on a large scale. So exergy analysis which is based on the First and Second Laws of Thermodynamics, can be applied to estimate the efficiency of energy conversion from industrial processes and sub-sector to international energy structure. It can be used to calculate theoretic energy demand in every consuming process and point out the maximum available saving potential. Exergy analysis can be used to estimate the quality of industrial waste in order to optimize the energy utilization and recovery via the so-called 'energy cascade'. This chapter will discuss the definitions and differences between energy and exergy analysis, as well as illustrating their advantages and disadvantages. Now exergy method has been widely employed to examine the energy consumption from the supply side to the end-users [1], particularly in continental Europe and North America. Hammond and Stapleton [1] analyzed the United Kingdom energy system and estimated of sector-weighted or 'lumped' parameters by exergy analysis. This study illustrates the advantages of the exergy method, and identified the improvement potentials for energy saving in the four sectors of the UK society, especially electricity generation. The exergy method suggest the main exergy losses is due to combustion, heat transfer and other thermal power processes [1] in industrial boilers, blast furnaces and other thermal process equipment. It is then possible to find effective ways, or develop relevant technologies to reduce, to recover or to avoid such exergy losses.

3.2 Energy analysis via the First Law of Thermodynamics

'Energy analysis' was developed in the 1970s after the oil crisis [7, 8, and 9], and is now widely used to assess the energy consumption and forecast energy demand in the future. The First Law of Thermodynamics indicates that energy cannot be created or destroyed, and can only be converted from one form to another form or transfered from one carrier to another carrier. According to this law, energy cannot disappear and only be transferred among the existing forms, so that humanity could have enough energy without developing new energy resources if the waste energy could be recovered. Actually, billions of tonnes of fossil fuel are consumed every year. Energy analysis is based on the principle of energy conservation: balancing energy inputs and outputs from a defined system. Energy analysis cannot give appropriate information to optimize the energy structure and modify energy intensive equipments and working procedures. In order to analyze the 'quality' of energy, exergy analysis must be employed. This is devised from the First and Second Law of Thermodynamics.

3.3 Exergy analysis by the First and Second Laws of Thermodynamics

3.3.1 Introduction

The concept of exergy was established from the middle of 1970s and developed in the 1980s [9, 10, 11 and 12]. The exergy is based on the First and Second Laws of Thermodynamics. The second law indicates that energy cannot change its form freely and has to transfer along some direction (down a temperature gradient), which gives rise to the degradation of energy quality. Exergy is the measurement of energy quality, and indicates the maximum useful work obtainable from an energy system at a given state in a specified environment. The loss of exergy indicates the degree of 'irreversibility' in energy transfer. An energy transfer process takes place in the direction of entropy increasing, and driven by changes in thermodynamic potential, such as pressure, temperature or voltage. The exergy conversion between the different thermal status is along irreversible direction without external force to drive and this kind of energy conversion can cause the exergy loss. In order to utilize energy effectively, especially thermal energy, the critical factor is to reduce the irreversible losses in the energy transfer processes, to utilize energy and to minimize it degradation. According to this principle, combustion and chemical reaction processes should be in a high temperature environment. Heat transfer to the environment, and energy loss by throttle and friction, should be avoided. The determination of irreversible processes is helpful for the effective utilization of thermal energy.

The energy analysis based on the First Law of Thermodynamics studies the quantity of energy conversion, transformation and consumption and compares the energy input and output. Energy method can find the energy consumption efficiency, which can guide the energy requirement in industry. However, energy analysis cannot point out the effective path of energy saving, because it cannot be used to analyze the processes of energy conversion and transformation. Therefore, it is unusable to determine how much energy is consumed by irreversibility factors, or where and how much energy can be potentially recovered and saved. On the contrary, the exergy analysis is useful tool to analyze the energy consumption in practical systems, which was developed [13, 14, 15, 16, 17 and 18] and widely used in industrial sectors from the 1980s [19, 20, 21and 22]. According to Hammond [37], energy analysis indicates the energy consequences of actions, but exergy analysis can point out the maximum available amount of energy in the energy system. Through exergy analysis, the quality difference of different energy resources can be found. For example, in a thermal-electricity generation process, the energy quality (energy or the ability to undertake work) of the primary steam is better than that of a recycle steam, in spite of the fact that their temperatures are adjacent.

3.3.2 Exergy concept and method

The word exergy is derived from the Greek *ex* (out or outer) and *ergon* (force or work) and the concept was first noticed in 1824 by Carnot in the relation of heat and work, which is defined as:

Exergy = work (ordered motion) or ability to do work (ordered motion)

Exergy is the maximum work which can be obtained from an energy resource or system in relation to the reference environment (or sink) [23]. The exergy from a system can be divided into physical exergy and chemical exergy:

Exergy = Physical Exergy + Chemical Exergy (5)

Physical Exergy

Physical exergy consists of mechanical exergy and thermal exergy and can be written as follows:

$E^{ph}= (U-U_0) + E^{ke} + E^{PT} +P_0 (V-V_0)-T(S-S_0)$ (6)

where E^{ke} is kinetic exergy and E^{PT} is potential exergy, which both equal their energy value in number.

$E_M=W$ (7)

Thermal exergy is determined by the reference environmental or 'dead' state, T_0 and P_0. The maximum work that a thermal system can offer between a hot resource T_h and cold resource T_c is the exergy value of the thermal system and is written as follows:

$E=Q (1-T_c/T_h)$ (8)

where Q is heat transferred from a hot resource to a cold resource. When the environment state is taken as the reference dead state, the output exergy can be written as formula (4):

$E=Q (1-T_0/T)$ (9)

In the case of heat transfer from high temperature side T_{high} to low temperature side T_{low} without power output, the thermal exergy contained in the transferred heat is:

$E^Q=Q (1-T_{low}/T_{high})$ (10)

Q is written as:

$Q=mC_p(T_{high}-T_{low})$ (11)

where C_p is the specific heat, and m is the mass flow of the working fluid.

Thus, exergy analysis provides of the thermodynamic quality of an energy carrier [24]. Which Van Gool (1987) defined in term of the ratio of exergy to enthalpy as follows:

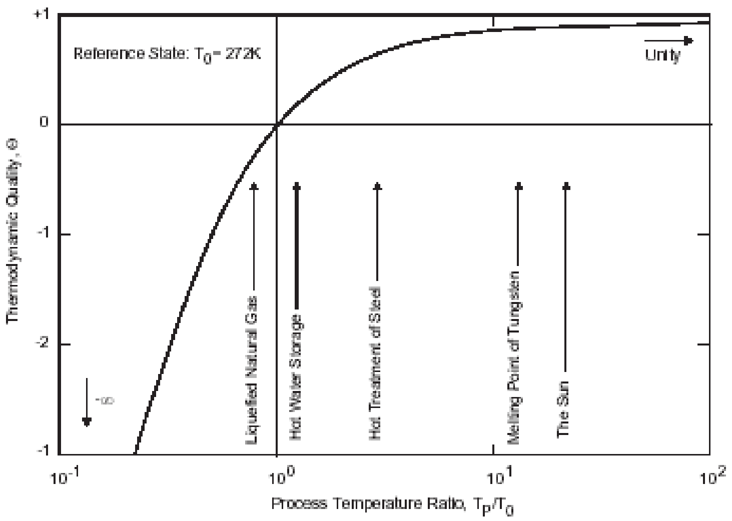
$\Theta = \frac{E}{H}$ (12)

O'Callaghan (1993) called the same parameter the 'exergetic potential'.

For electricity: $\Theta = 1$

And for process heat: $\Theta = (1-T_0/T_p)$

Figure 7 describes the relationship between temperature and Θ.



Figuer7: Temperature dependence of thermodynamic quality.

(Source: Hammond [37])

Chemical Exergy

Chemical exergy is a very important part that must be considered during exergy analysis. In industrial production processes, besides electricity, thermal power comes from burning hydrocarbon fuels; the main energy input used by most industrial sub-sectors. Moreover, in some sub-sectors, such as chemicals and the iron making process, chemical reactions among different raw materials release or absorb energy and degrade exergy. In the case of the combustion of hydrocarbon fuels, the standard chemical exergy released from combustion can be calculated by considering an idealized reaction between the hydrocarbon fuel and the oxygen in the environment forming CO_2 and liquid water [25, 26]. According to Göran Wall's study [28], the specific chemical exergy of ideal gas produced by fuel burning is equal to the heating value of the gas at a reference dead state and can be described as formula [9].

$$e_k^{ch}=-RT_0 \ln x_k \tag{13}$$

And for the calculating of the chemical exergy of mixture, formula (13) is used for specific exergy [25].

$$e_m^{ch}=(\sum x_k\, e_k^{-ch}+ RT_0 \sum x_k \ln x_k)/M \tag{14}$$

Actually, in most industrial sub-sectors, except the chemicals industry, the main chemical reaction is the combustion of fossil fuels at high temperature, steam generation, space heating, and power generation. The specific exergy of hydrocarbon fuel combustion can be calculation by formula (14) [29].

$$\varepsilon_f =\gamma_f H_f \tag{15}$$

In formula (15) γ_f denotes the fuel exergy grade function, defined as the ratio of fuel chemical exergy and the last term in (15) is the fuel Higher Heating Value H_f [29], (or Gross Calorific Value in European useage). Table 3 shows some typical values of H_f, ε_f, and γ_f for the fuels encountered in the present study. Usually, the specific chemical exergy ε_f of a fuel at T_0 and P_0 is approximately equal to Higher Heating Value H_f [29].

Fuel	H_f (kJ/kg)	ε_f(kJ/kg)	γ_f
Gasoline	47,849	47,394	0.99
Natural gas	55,448	51,702	0.93
Fuel oil	47,405	47,101	0.99
Kerosene	46,117	45,897	0.99

Table 3: Energy and exergy efficiencies for some processes for some ideal combustion comparison [29]

From the above discussion, it is clear that different forms of energy have different energy qualities. Energy quality means the ability of energy transferring from one form to another form. Göran Wall gives the assessment of several kinds energy in his study (see Table 4) [30]. Here it is clear that electricity is a high quality energy carrier which can be used to undertake work

Energy form	Exergy factor
Mechanical energy	1.0
Electricity energy	1.0
Chemical energy	About1.0†
Nuclear energy	0.95
Sunlight	0.93
Hot steam(600°C)	0.6
District heat(90°C)	0.2-0.3‡
Heat at room temperature(20°C)	0-0.2‡
Thermal radiation from earth	0

Table 4: The exergy factor of some common energy forms [30]

† May exceed 1, due to definition of system boundaries and final states

‡Depend strongly on the environment temperature

Exergy Budget and Efficiency

The above discussion illustrates the exergy concept and its calculations for different kinds of energy forms. Real industrial processes are complicated, so that a bulk property, such as the exergy efficiency of the processes is used. This can reveal the exergy loss in energy flow and indicate constructive suggestions for energy saving.

The energy forms required by the industrial production are various, and almost all industrial processes operate at a stable status: a fixed temperature, a fixed pressure, a fixed space of working performance, and a fixed time for every working procedure [24]. Raw materials and energy flows into the industrial system from one site and leaves from the output end in the forms of products and waste. The exergy analysis of industrial processes is complicated, although steady flow occurs across the boundaries. The most important factors that can affect the exergy analysis results are therefore the definition of boundaries and the reference environment states. In addition, kinetic and potential exergies can be assumed to be negligibly small [25] in a steady flow state, so physical exergy is simplified:

$$E = (H-H_0) - T_0\,(S-S_0) \qquad (16)$$

where, E is the exergy, H is enthalpy and S is the entropy.
And the exergy budget can be described as

$$\sum \varepsilon_{in} m_{in} - \sum \varepsilon_{out} m_{out} - \sum (E^Q - E^w) - I = 0 \qquad (17)$$

where, E^Q and E^W mean exergy transfer by the forms of heat Q and mechanical work W. Where, ε is specific exergy of items, which consist of physical exergy and chemical exergy. I is the exergy consumption or exergy destroyed by some irreversibility [1], which is given by

$$I \equiv \Delta E_{loss} = E_{in} - E_{out} > 0 \qquad (18)$$

And exergy efficiency is defined as the proportion of utilized exergy in whole exergy
Exergy efficiency = Utilized exergy/ whole exergy

$$\Psi = E_{out} / E_{in} = 1 - I/E_{in} < 1 \qquad (19)$$

It could be found that equation (19) is like the formula of energy balance which is made based on the First Law of the Thermodynamics. Exergy analysis is a very useful tool to monitor the process of energy conversion, and find the location and quantity of exergy loss during the energy conversion process. Van Gool (1992) has noted that the maximum improvement in the exergy efficiency for a process or a system is obviously achieved when ΔE_{lost} is minimized [24]. Van Gool suggested that it is useful to employ the concept of an exergetic 'improvement potential ', IP, when analysing different processes or sectors of the economy [24]. It is given:

$$IP = (1-\Psi)\,(E_{in} - E_{out}) \qquad (20)$$

3.3.3 Application of exergy analysis

Exergy analysis is widely used in continental Europe and North America. Many studies have been undertaken over the past three decades. From these studies, it is clear that the main exergy degradations arise in thermal processes, such as combustion, heat transfer and thermal-power process. Hammond and Stapleton [1] pointed out that, for the United Kingdom in the late 1990s, final demand in the domestic and transport sectors, together with electricity generation, accounted for nearly 80% of exergetic improvement potential. They suggest that it is necessary to focus attention principally on making better use of space heating systems, improving the operating efficiency of 'power' plant, and reducing thermodynamic losses in transportation systems that are presently dependent on IC engines [1]. In order to study the industrial sector more closely, they divided the industrial sector into four broad categories according to their working temperature [1]: low temperature (T_p<394 K), medium temperature (T_p =394-692 K), high temperature (T_p > 692 K), and mechanical drives. Typical energy and exergy efficiencies in these categories are illustrated in Fig. 8.

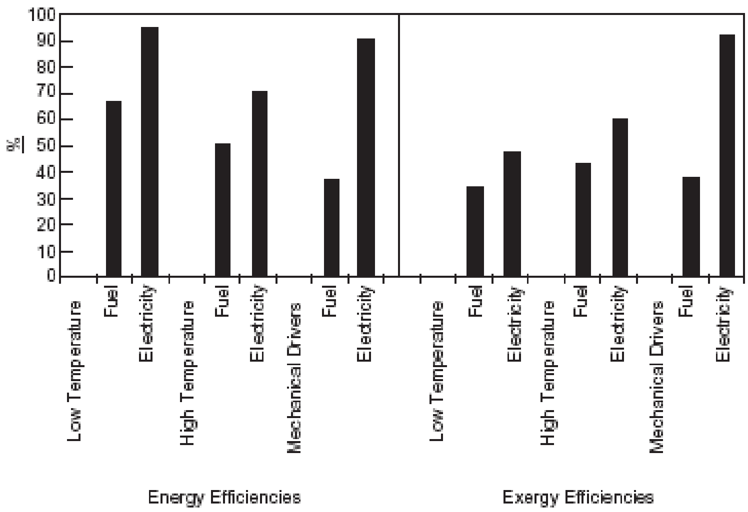


Fig 8.Thermodynamic efficiencies of industrial processes [1]

This study illustrated that in the industrial sector, especially the subsectors which have the requirement of high temperature for their production, like iron and steel industry, sugar industry, glass industry and cement industry, thousands of tons of fuel are combusted everyday to support enough heat for the demand of drying, melting, forming and other needs. If a little improvement of exergy efficiency can be obtained, lots of energy and fossil fuel will be saved in these energy intensive industries. Comparing with the large exergy loss due to combustion in the thermal-power sector and space heating in the domestic sector, the proportion of exergy loss in the whole energy input of British industrial sector is small; however, it is still significant that the energy consumption model in the industrial sectors have the characters of concentration, temperature varieties and the forms of energy varieties [1]. In the domestic sector, the biggest energy consumer, most of exergy loss is in space heating, hot water and kitchen demand by burning natural gas at low temperature or using electricity directly for low temperature heat demand, which has been proved to be the most un-effective method to use energy [1]. Moreover, the energy consumption in every family is small and happens randomly, so it is different to control and manage the energy consumption in every family. In the present study, the exergy method will be used to track the energy flow in iron and steel industry and find possible energy saving potential.

3.4 Summary

The First Law of Thermodynamics denotes that energy can neither be created nor destroyed, and can only be converted from one form to another form without any loss in quantity. In contrast, the Second Law of Thermodynamics denotes the rules of energy transfer and conversion. According to the Second Law of Thermodynamics, the transfer and conversion of energy has to follow a certain direction, and involves irreversible processes. The factor which decides the direction of energy transfer and conversion is entropy. The Second Law points out that energy transfer and conversion are always along the direction of entropy increasing. If the reversible process is required, it must be at the expense of entropy increasing in the system or in the whole environment. The increase of entropy means the degradation of energy quality. So according to the first law of thermodynamics, there is no energy loss in quantity during energy consumption process, while according to the Second Law, the essence of energy transfer and conversion is the degeneration of energy quality. The index that is used to denote the quality is exergy. This chapter discusses exergy using the 1st and 2nd Laws of Thermodynamics. The introduction of exergy analysis displays the advantages of using exergy to analysis energy system and energy consumption. By the exergy analysis, the energy saving potential in the UK energy system can be clearly found, which can guide energy utilization and improve energy efficiency.

4. Energy consumption in British industrial sector

4.1 Introduction

British industrial sector consumed 27.5 million tones of oil equivalent energy in 2010, which accounted for near a fifth of all UK energy consumption (See Figure 9&10). After the first oil crisis in 1973, great changes have taken place in the industrial sector with the final energy demand decreasing by 56% during the past four decades (see Figure 9)[31]. The proportion of energy consumed in traditional energy-intensive sectors has decreased significantly during the past decade.

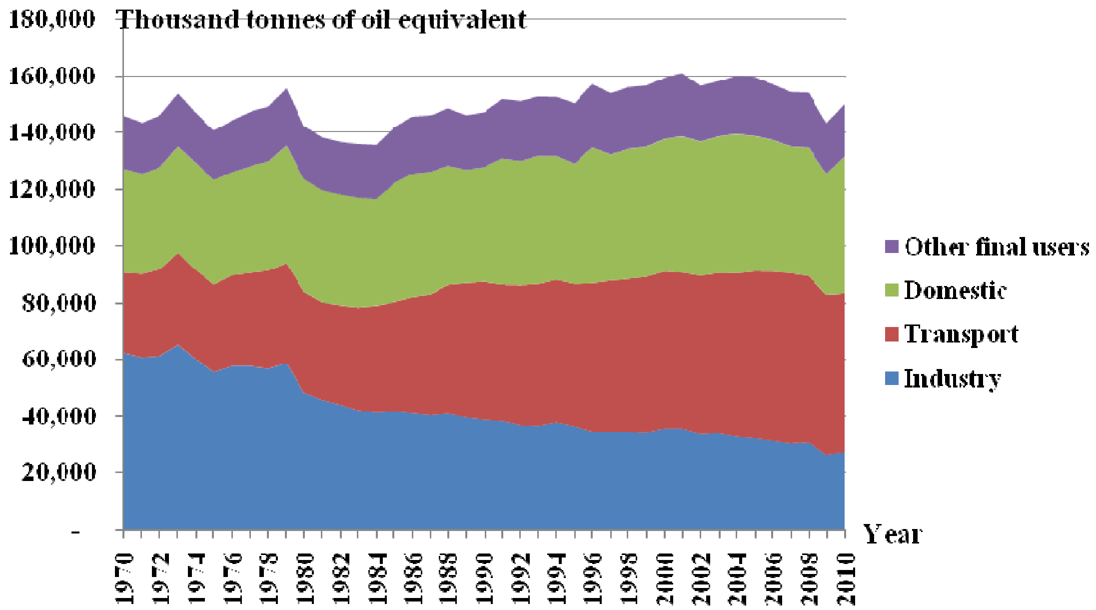


Figure 9: Energy consumption by final user, 1970 to 2010 (Source: DECC 2011, [77])

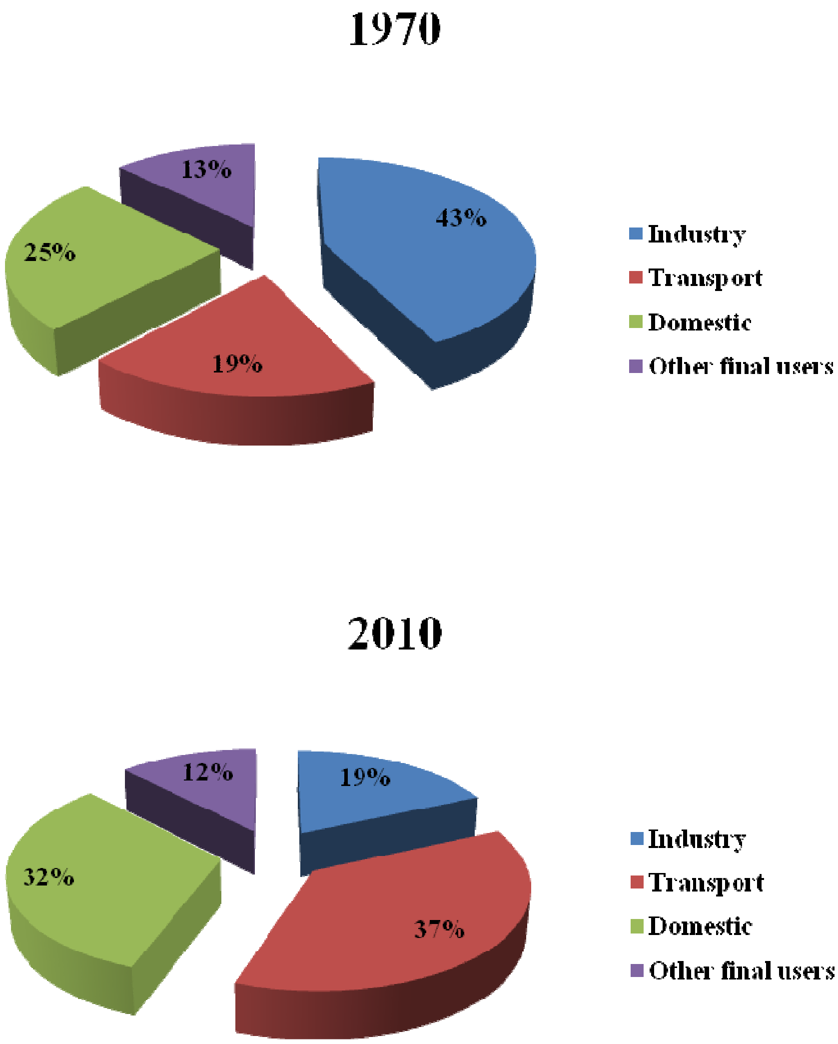


Figure 10: Percentage sector shares in total energy consumption, 1970 and 2010 (Source: DECC 2011, [77])

4.2 Energy consumption structure and status in the British industrial sector

According to the SIC (2003), the UK industrial sector is divided into 23 main trades. In the whole British industrial sector, seven sub-sectors consumed almost 64% of the energy input in the whole industry system (see Table 5 and Figure 11), and the largest energy consumer in the UK industrial sector was the manufacture of coke, refined petroleum products and nuclear fuel in 2010. It consumed 14.4％ of all industrial energy use (see Figure 12), while the manufacture of chemicals, chemical products and man-made fibres consumed a further 12.8 %, and occupied the second position. According to the statistics given by the DECC, one fifth of all energy used in the food, drink and tobacco industry was consumed by sugar production, while a further 13% was used for making beverages and another 10 % for the production, processing and preserving of meat and meat products [31]. The proportion of energy consumed by the iron and steel industry, decreased 7% in 2009 compared with that in 1990 (see Figure 13).

Thousand tonnes of oil equivalent

SIC (2003) code	Description	Energy consumptions
23	Manufacture of coke, refined petroleum products and nuclear fuel	4,490
24	Manufacture of chemicals, chemical products and man-made fibres	4,016
15	Manufacture of food products and beverages	3,181
26	Manufacture of other non-metallic mineral products	2,483
27	Manufacture of basic metals	2,190
21	Manufacture of pulp, paper and paper products	1,834
25	Manufacture of rubber and plastic products	1,749
	Total	19,942
	other sub-sectors	11,246
	All industry	31,188

Table 5: Industrial energy consumption by end users in 2010 (Source: DECC 2011, [77] and the Office for National Statistics' Purchases Inquiry)

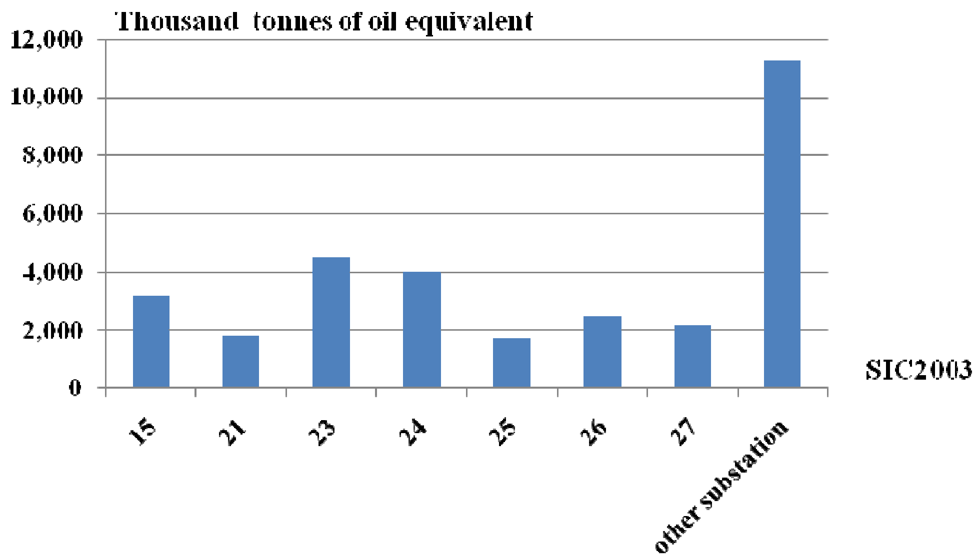


Figure 11: Energy consumption in the main energy intensive industries in the UK in 2010(Source: DECC 2011, [77] and the Office for National Statistics' Purchases Inquiry)

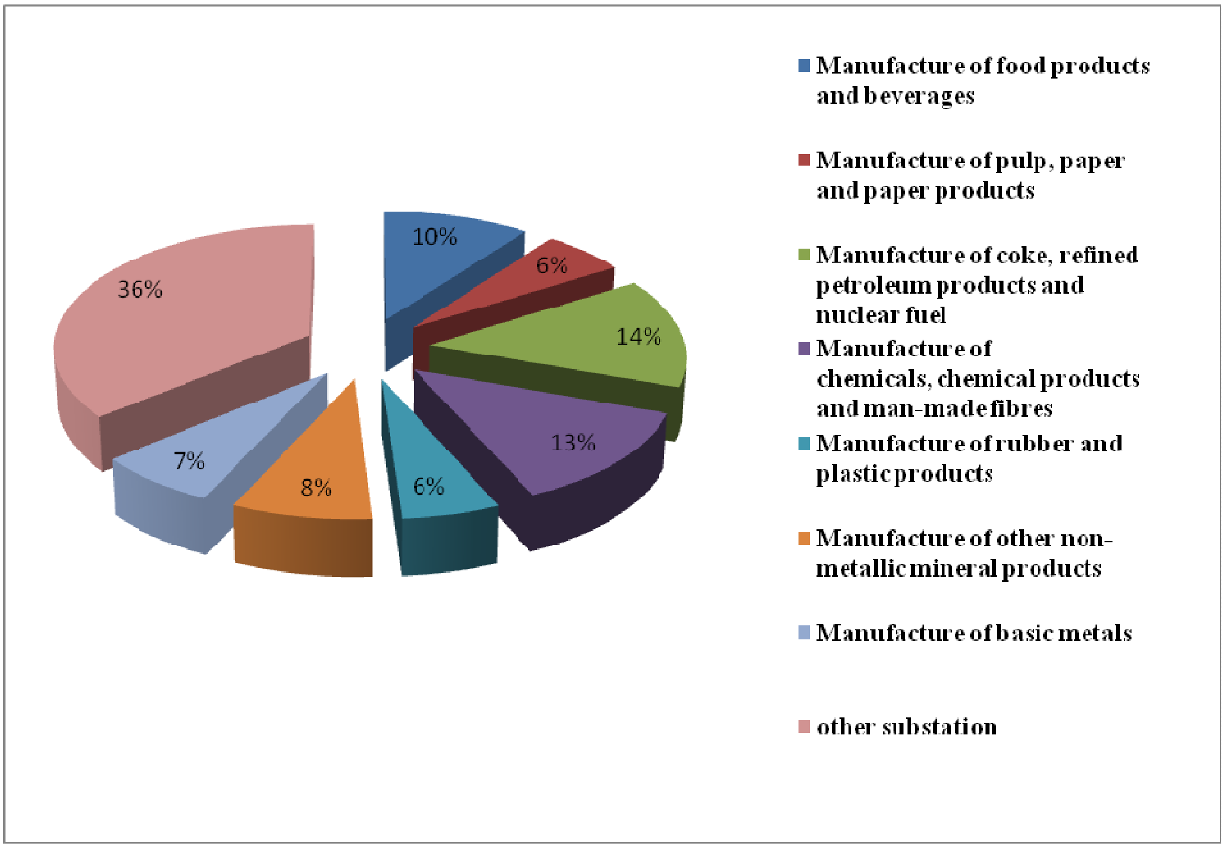
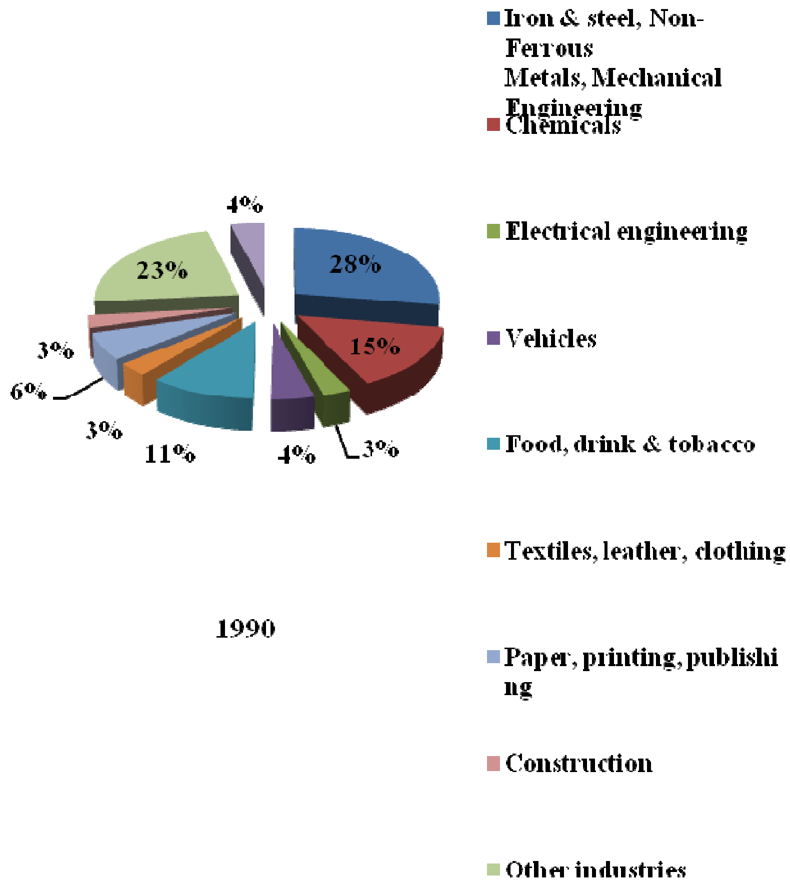


Figure12: Industrial energy consumption by end users in 2010. (Source: DECC 2011, [77] and the Office for National Statistics' Purchases Inquiry)



4%
23%
28%
15%
3%
6%
3%
11%
4%
3%
1990
Iron & steel, Non-Ferrous Metals, Mechanical Engineering
Chemicals
Electrical engineering
Vehicles
Food, drink & tobacco
Textiles, leather, clothing
Paper, printing, publishing
Construction
Other industries

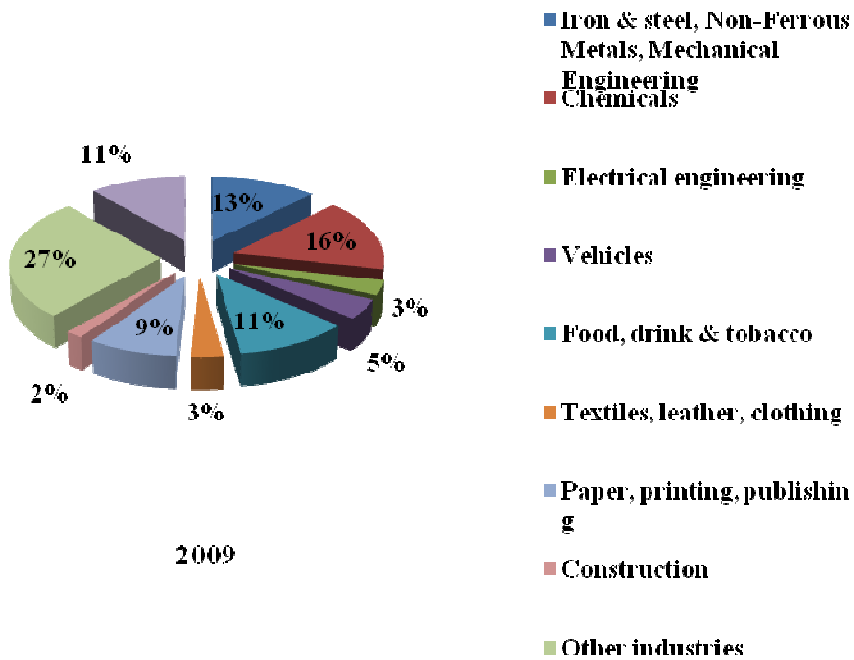


Figure 13: Percentage of energy demand of main energy-intensive industries 1990 and 2009 (Source: DECC 2011, [77] and the Office for National Statistics' Purchases Inquiry)

The main forms of energy utilized by the industrial sector are fossil fuel and electricity. However, these forms cannot be used directly by the industrial processes. Light, thermal energy and power for mechanical drive are what the industrial processes actually need. So when the fossil fuel and electricity enter the industry system, they have to be converted into other forms (see Fig 14) via boilers, motors, turbines, heaters and other devices. Electricity is a high grade energy carrier and can in theory be converted into any other forms of energy service. On the contrary, the only way to obtain energy from fossil fuel is combustion to obtain thermal energy. Combustion and heat transfer are two main irreversible processes in the conversion processes. In 2010, 86% of energy input in the British industrial sector was in terms of chemical fuel, for combustion **(Source: DECC 2011, [77])**. On the other hand, in the British industrial sector, 73% of the total energy input was used for process heating operations in 2010, which included low temperature process, high temperature process, space heating and dry/separation, and only 6.4% of energy input is used to supply power to drive motors, compressors and so on (see Table 6). Besides the fossil fuel, about 40% of electricity consumption in the industrial sector is used for process heating.

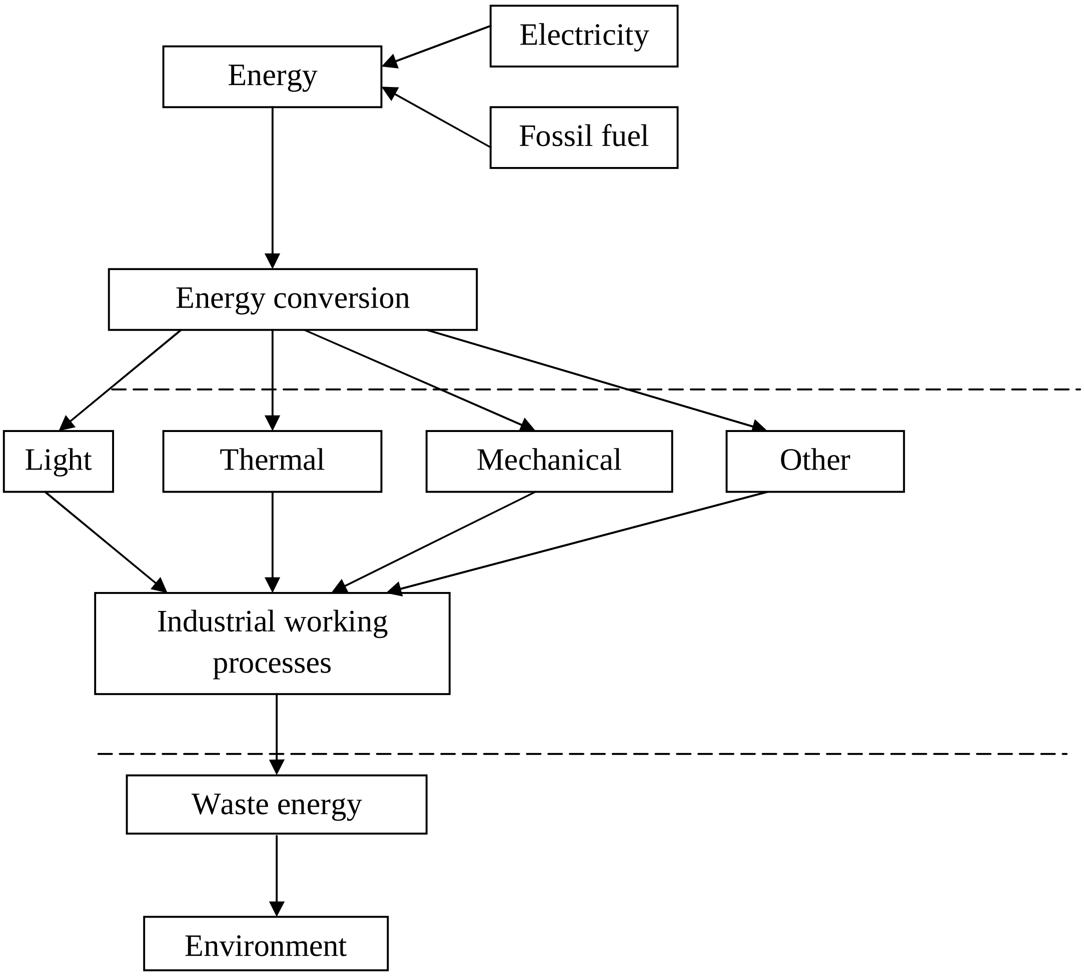


Figure 14: Energy flow model in the British industrial sector

Since the thermal energy is the biggest energy demand of the British industrial sector, the analysis of existing thermodynamic processes in major energy-intensive industries is an effective approach to find out the greatest energy saving potentials and help the whole industrial system reduce energy demand. Exergy analysis is a useful tool for analyzing the thermodynamic systems. In a combustion process, the exergy loss is decided by the temperatures of combustion and reactants. The same quantity of fossil fuel burnt at different temperatures can release different amount of thermal exergy, the higher the temperature of combustion is and the smaller the exergy loss will be. In order to analyze the exergy consumption of the British industrial sector, Hammond & Stapleton [1] divided the multitude of thermodynamic processes into four broad categories: low temperature (T_p <394K or t_p <120.85℃), medium temperature (T_p=394-692K or

t_p =120.85-418.85℃), high temperature (T_p>692K or t_p>418.85℃) and mechanical drive. Table 7 gives the ranges of temperature of process heating operation in the main energy-intensive industries. In Energy Consumption in the United Kingdom published by the DIT [1], the energy consumption in the industrial sector is divided into nine major processes in table 6. In Energy Consumption in the United Kingdom, the energy processes in coke ovens, blast furnaces and other furnaces, kilns and glass tanks are high temperature process uses of energy are and other heat demand for industrial processes, such as heating and distillation in the chemicals sector; baking and separation processes in food and drink; pressing and drying processes in paper manufacture; and washing, scouring, dyeing and drying in the textiles industry, are low temperature processes. The other energy demands for pumping, fans, machinery drives, compressors (for both compressed air supply and for refrigeration) and conveyor systems belong to motive power consumption [3]. Acoording to the temperature in the real industrial processes, the high temperature process defined the DTI is high temperature processes in Hammond & Stapleton's categories [1]. The Low temperature processes in table 6 is energy comsumption prcesses in medium temperature and low temperature processes defined by Hammond & Stapleton diveided [1]

Thousand tonnes of oil equivalent

<table>
<tr><th>Energy conversion process</th><th>Energy consumption</th><th colspan="2">Percentage of total energy consumption</th></tr>
<tr><td>Low Temperature Process</td><td>8,782</td><td>32.5%</td><td rowspan="4">73.%</td></tr>
<tr><td>High temperature process</td><td>4,269</td><td>15.8%</td></tr>
<tr><td>Space Heating</td><td>3,053</td><td>11.3%</td></tr>
<tr><td>Drying / Separation</td><td>3,607</td><td>13.4%</td></tr>
<tr><td>Motors</td><td>3,083</td><td>11.4%</td><td rowspan="3">16.4%</td></tr>
<tr><td>Compressed Air</td><td>870</td><td>3.2%</td></tr>
<tr><td>Refrigeration</td><td>480</td><td>1.8%</td></tr>
<tr><td>Lighting</td><td>252</td><td colspan="2">0.9%</td></tr>
<tr><td>Other</td><td>2,618</td><td colspan="2">9.7%</td></tr>
<tr><td>Total</td><td>27,014</td><td colspan="2">100%</td></tr>
</table>

Table 6: Energy consumption during different processes in 2010 (Source: DECC 2011, [77] and the Office for National Statistics' Purchases Inquiry)

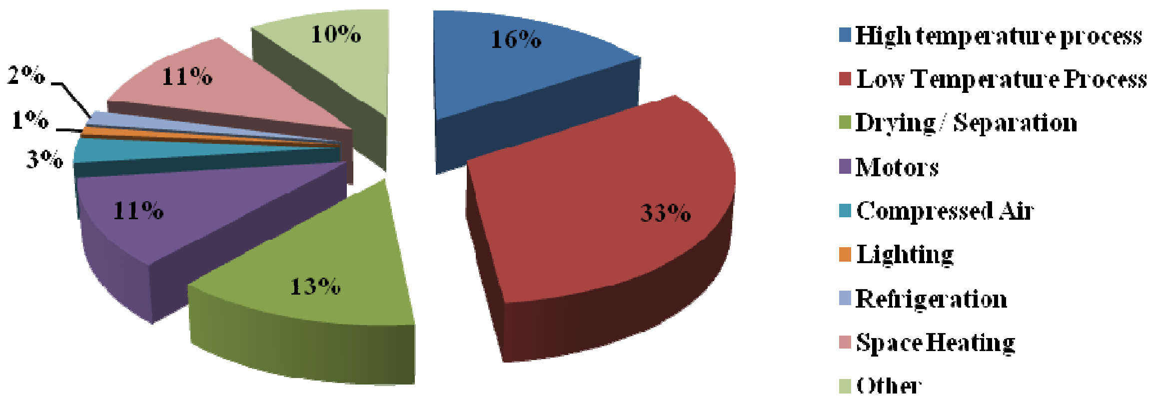


Figure 18: Percentage of energy consumption in different processes in 2010 (Source: DECC 2011, [77] and the Office for National Statistics' Purchases Inquiry)

In Table 6 & Figure 18, 32.5% of all the energy input were used for the low temperature requirements in the UK industrial sector in 2010, which are below 418.85℃ the classification made by Hammond & Stapleton [1], The exergy consumption in low temperature, both from fossil fuel and electricity, made significant exergy waste according to the exergy efficiency analysis (see Table 7 [32]).

Process-heat temperature range(℃)	Fossil-fuel heating efficiency (%)		Electricity heating efficiency (%)	
	η_f	Ψ_f	η_e	Ψ_e
Low (<121)	65	0-16	100	0-24
Medium (121-399)	60	15-33	90	22-60
High (>399)	50	28-50	70	39-70

Note that T_0 = 25℃

Table 7: Values of energy and exergy efficiency for fossil-fuel and electricity heating processes at several ranges of process heat temperature [32]

Despite the fact that thermodynamic processes have high exergy and energy efficiency when operating at high temperature, actually only 15.8% of energy input is used for high temperature processes in the UK in 2010 (see Table 6). Low temperature and medium temperature processes consume most of the energy input and serve for most of the industrial processes.

Chemical fuel combustion and electricity heating are the two ways for heat demand in the industrial sector. Table 7 indicates the energy and exergy efficiency for these heating processes at different ranges of process heating temperature. It is obvious that heating by electricity have higher values for both energy efficiency and exergy efficiency than by chemical fuel combustion, but it should be noticed that the exergy loss caused by electricity generation is quite high and excludes in the electricity heating. The advantages of electricity heating are in terms of small devices, low equipment investment cost, and easy temperature control. This method is convenient and flexible for some small factories, which do not have huge heat demand. Getting heat by burning fuel in industrial boiler or furnace is still the main option for the industrial processes with large heat demand. However, the combustion in industrial boiler and furnance is a high temperature process [3], some industrial sub-sectors require low temperature heat, such as steam and heat water, which belong to low and medium temperature processes in Hammond and Stapleton's classification [1]. Supplying hot water and low temperature steam with industrial boiler need heat transfer between high temperature flue gas and cold feed water and high quality thermal energy becomes low quality thermal enery, which causes huge exergy loss As shown in Figure 11 and 12, over 64% of all the energy input for the industrial sector is consumed by the seven sub-sectors, most of which are the largest users of low temperature heat, such as the paper industry, chemical industry, food industry, and petroleum industry [33]. The effective way to meet large amounts low temperature demand without large exergy loss is adopting CHP (combined heat and power) system. In CHP system, high thermal exergy is used for power generation and the waste heat, such as heat in exhaust gas and cooling water, is recovered for heat demand. CHP system can use coal, natural gas, biogass, biomass, etc. as fuel. Currently the energy efficiency of advanced CHP system using gas engine can reach or exceed 90% in the UK [79]. The Sector 4.3 is a utilization of an industrial boiler and CHP system in the sugar industry

4.3 Energy and exergy analysis of sugar industry (literature review [34])

Food products and beverages industry are the biggest consumer of low temperature thermal energy in the British industrial sector. In the whole food and beverages industry, the sugar industry is a classic low temperature heating process. During the process of sugar generation, a large quantity of low temperature steam, with the temperature of 130℃~140℃ is required for raw juice production, juice clarification, juice concentration and sugar refining [34]. Steam is mainly used for low temperature heating, the requirement of the steam pressure is not high. The steam with low temperature and low pressure has a low grade exergy value. In order to avoid exergy loss, British sugar manufacturers adopts CHP systems to generate and supply steam and power, not burning fossil fuel in boiler to produce steam only. By 2010, the installed capacity of CHP systems owned by the biggest British sugar manufacturer, British Sugar plc, has achieved 184 MWe, much more than other food, beverages and tobacco manufacturers (Source: DECC 2011, [77]). In 2007, the energy consumption of the UK sugar industry (SIC 1583) was 104 thousand tonnes of oil equivalent, 73.5% of which was natural gas (Source: DECC 2011).

In the modern sugar industry, according to the energy flow, the production process can be divided into two main sections, heat and power supply system and sugar production system (see Figure 19). Due to the generation, utilization and recovery of steam, a series of thermodynamic processes operate during the sugar production. Table 8 and 9 are detailed information about energy and exergy loss distributions in sugar industry [34]. Tekin & Bayramoglu [34] provided an analysis based on research in a Turkish sugar factory. The production processes and data are typical in large modern sugar manufacturers; this case is used as a reference to analyze the energy and exergy balance in the British sugar production. However, it should be noticed that one important difference between this case and the British sugar industry is the fuel feed into the CHP system, which is coal in Turkey shown in Table 8 and 9, but natural gas in the British sugar factories. In Table 8, the biggest energy loss is the heat rejected to the environment, including heat rejected to the environment with waste, which takes 63% of total energy loss, and heat rejected to the environment from equipment and piping surfaces, 30% of total energy loss. The energy loss is that energy changes its form or status to make it difficult to be recovered and re-used. For example, the biggest loss is the sensible heat of coal ash heat of combustion of unburned coal, which comes from chemical energy in fuel via combustion process and goes into environment in forms of thermal energy. Figure 9 displays energy transfer and energy loss in every process units and 42% of the energy losses occur in steam-power system due to various sensible heats with waste. Exergy losses analysis in Table 9 also shows that most of the exergy losses, 75%, occur in steam-power system, but the biggest exergy loss from steam-power system is due to the combustion of fuel in steam system. The second biggest exergy is in steam generator, 16% of total exergy losses. Two main irreversible processes, combustion and heat transfer, course these two major exergy losses.

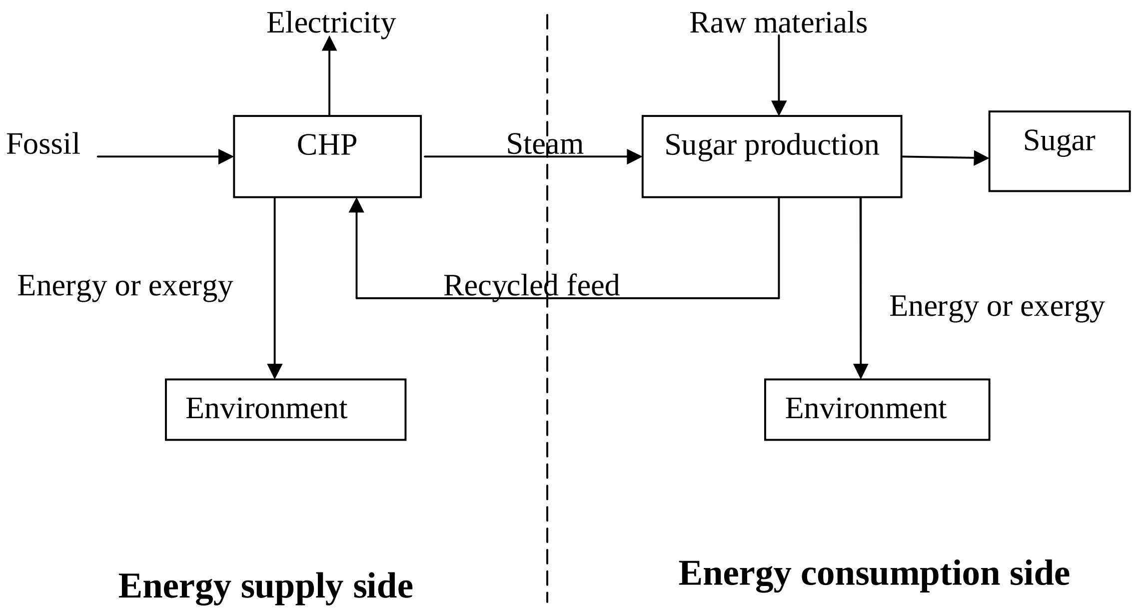


Figure 19: Simplified energy structure in sugar production

In the Tekin & Bayramoglu [34] study, it is shown that the biggest loss either energy or exergy occurs in CHP plant, but the contents of these two kinds of loss are different. For the supply side, the main energy input is fossil fuel with a high exergy value, 24.1 GJ per tonne of coal or 35.6 MJ/m^3natural gas. On the other hand, the main energy use for the energy consumption side, which is also a part of the energy output of CHP plant, is the steam with low temperature and low pressure, which carries a low exergy value. In the sugar production process, the maximum exergy that can be used is in theory all the exergy contented in the steam. So the results of Tekin & Bayramoglu [34], 74% exergy loss occurs in the CHP system and only 16.05% goes into the right side serving the sugar production (see Figure 21). Moreover, the details of exergy loss distribution are indicated by the exergy analysis for every operation. Combustion in the industrial boiler, steam generation and the waste from the boiler mainly composed by coal and stack gases, are the four main exergy losses. From the scope of the operations in the whole sugar factory, all of these exergy losses, in both the CHP side and the sugar production side, are caused by two irreversible processes, chemical reaction (combustion) and heat transfer, so analyzing the change of exergy in these irreversible processes and reducing the negative factors, such as heat transfer between large temperature differeces, which cause exergy loss, is the key to improving exergy efficiency and then saving energy.

(a) According to process units	
1.Raw juice production	2.40
2.Juice clarification	10.80
3.Juice concentration	0.87
4.Sugar refining	7.17
5.Vacuum system	14.94
6.Hot water processing-storage	7.77
7.Steam-power system	31.70
(b) According to plant locations at which losses occur	
Ⅰ.Heat rejected with wastes to the environment	
Sensible heat of coal ash and heat of combustion of unburned coal	23.06
Sensible heat of stack gases	7.00
Sensible heat of waste slurry of $CaCO_3$	1.40
Sensible heat of waste slurry of un-slaked CaO and residue	0.02
Sensible heat of excess CO_2 from the carbonator	0.44
Sensible heat of humid air from cooling tower	14.94
Sensible heat of humid air from the granulator	1.00
Ⅱ.Heat rejected from equipment and piping surfaces to the environment	
From air cooled crystallizer	5.17
Heat lost by convection from all equipment and piping surfaces	17.40
Ⅲ.Energy loss in steam turbine	1.65
Ⅳ.Others	3.50

Table 8: Energy loss distributions, as percentages of plant input [34]

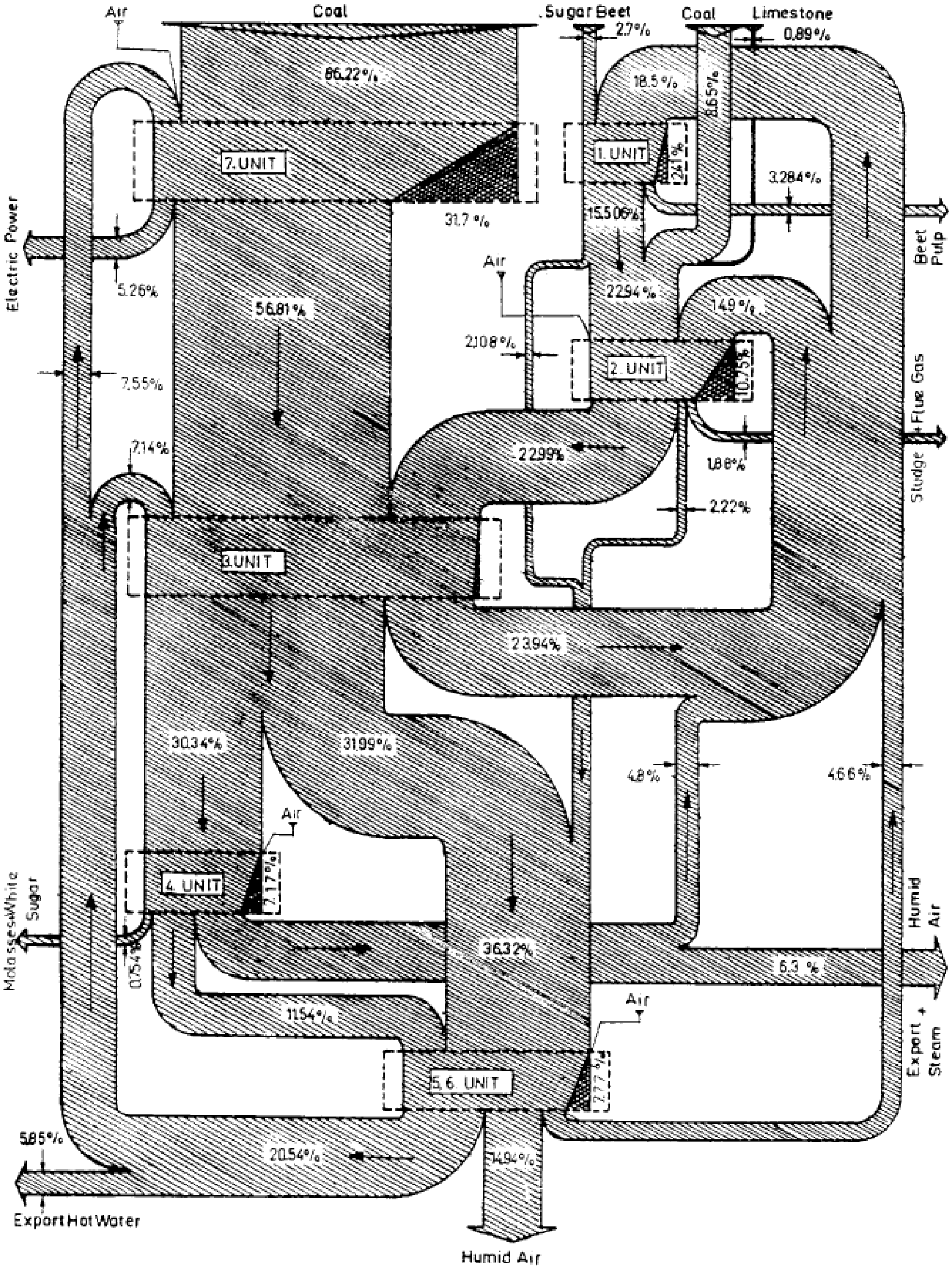


Figure 20: Energy band diagram of sugar industry [34]

(a) According to process units	δB_i	ε_i
1.Raw juice production	2.0	2.40
2.Juice clarification	7.0	7.12
3.Juice concentration	6.0	6.12
4.Sugar refining	2.5	2.55
5.Vacuum system	3.4	3.46
6.Hot water processing-storage	2.7	2.75
7.Steam-power system	73.1	74.40
Subtotal	96.7	98.44
Ψ		1.56
Total		10.00
(b) According to plant locations at which losses occur		
Ⅰ.Chemical reactions		
Combustion of fuel (coal) in steam generator		36.00
Others (limestone calcination, lime slaking, lime carbonation)		4.40
Subtotal		40.40
Ⅱ.Indirect heat transfer over a finite temperature difference between process fluids		
In heat-exchangers		1.60
In steam generator		15.00
In evaporators and vacuum pans		4.20
Subtotal		20.80
Ⅲ.Exergy of heat lost to the environment		
From equipment and piping surfaces		2.30
From air cooled crystallizer		0.30
Subtotal		2.60
Ⅳ.Mass and heat transfer		
In evaporator and vacuum pans		2.00

In barometric condenser	1.10
In mixing of hot water streams of different qualities	1.08
Saturation of turbine exit steam with water	0.70
Expansion of hot water streams in niessners	0.59
Mixing of different quality syrup streams in sugar refining	0.18
Subtotal	5.65
Ⅴ.Exergy of waste streams	
Coal ash	9.30
Stack gases	7.40
Humid air from cooling tower and granulator	1.00
Waste slurry of $CaCO_3$	0.10
CO_2 gas carbonator	0.30
Subtotal	18.10
Ⅵ.Exergy loss in steam turbine and turbo-pumps	3.45
Others	5.70
Total	96.70

Table 9: Exergy loss distributions, as percentages of plant input [34].

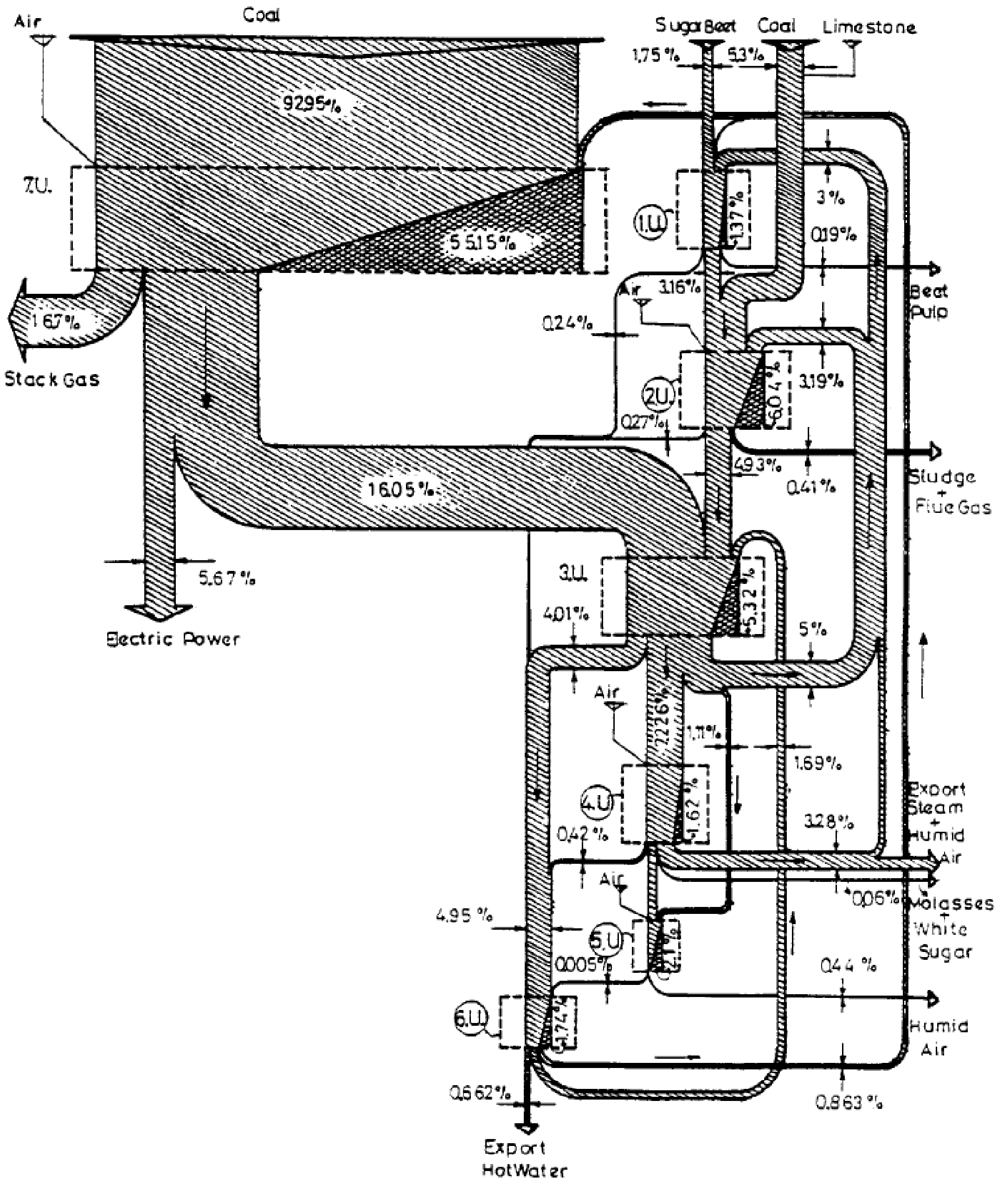


Figure 21: Exergy band diagram of sugar industry [34]

Fuel combustion, as an oxidation reaction, is a complex irreversible process and makes the biggest exergy loss in whole system. But this process is still widely used for steam generation because of easy operation and low cost based on current technologies. Combustion is a dramatic reaction between flammable components and oxygen. It is because of the dynamic equilibrium mechanism in chemical reaction, when superfluous oxygen joins the reaction, the old balance should be broken and more fuel will be burned to generate more resultants in order to establish the new balance of the concentrations of reactants and resultants [80]. So improving the oxygen concentration in the air can facilitate fuel burning completely. The temperature of combustion is another important factor affecting exergy efficiency. Table 10 gives the relationships between the temperature and the exergy efficiency. Since natural gas is the main fuel used by the industrial boilers in the British sugar plants, preheating natural gas and combustion air with hot exhaust gases can improve exergy efficiency significantly. In the UK, considering that the major fuel used by sugar plants is natural gas, using large size CCGT technology and extracting steam from a steam turbine as heat resource of sugar generation are the most effective methods of improving energy efficiency based on state-of-the-art technology.

Combustion temperature(℃)	Air temperature(℃)	Exergy budget (%)	Energy balance (%)
1000	20	56	100
	800	75	100
1200	20	60	100
	1000	79	100
1400	20	63	100
	1200	82	100

The case of approximately equal physical properties for air and combustion gas and simplified omission of fuel weight in combustion gas, ambient temperature of 20 ℃, combustion loss of 0%.

Table 10: Exergy analysis of combustion process [35]

The recovery of waste thermal energy is a method of reducing exergy loss from the end of the energy flow. In the sugar industry, the major wastes heat are contained solid and gaseous waste of combustion, recycling steam and hot water. In the UK sugar industry, because the major fuel used by most of sugar plants are natural gas, 73.5% in 2007 (Source: DECC 2011), most of the waste from the boiler is hot stack gas, which can be recovered more easily than the thermal energy in coal ash and other solid waste. Although the thermal exergy values in these wastes are not high, they still have higher temperature than original natural gas. Recovering the thermal energy to preheat fuel, combustion air, feed water and other low temperature flows before they enter heat exchangers can raise the combustion temperature and reduce the temperature difference in heat exchangers, so from the scope of energy saving, this method can use the waste thermal energy to save the energy consumption of preheating, and from the scope of exergy, this method reduces most exergy losses in two major irreversible processes, combustion and heat transfer. For other chemical reactions, the best way to reduce the exergy losses in these irreversible processes is adopting new technologies to avoid these reactions, such as a suitable membrane separation process, which can replace the old liming-carbonation method for raw juice clarification [34].

From this case study, it is clearly shown that CHP system has great advantage for saving energy compared with steam generation by an industrial boiler directly. Now, CHP systems have been the main choice in the modern factories with large amount of low-and medium-pressure steam demand, such as pulp and paper industry, food industry, and chemical industry. In the UK, by the end of 2010, the total installation of large scale CHP schemes are 5989 MWe (Source: DECC 2011, [77]). Current CHP systems are divided according to turbine types, steam turbine based systems and gas turbine based systems. In the case discussed above, the CHP system uses coal as fuel and is based on a back pressure steam turbine. In a CHP system based on a steam turbine, fuel is burnt in the industrial boiler to generate steam to drive a steam turbine for electricity generation and the exhaust steam from turbine or the extracted steam from the high-and medium-pressure cylinders of the steam turbine is supplied to the industrial processes. A CHP system based on gas turbine technology generates low- and medium-pressure steam in a waste heat boiler using the flue gases of a gas turbine [33]. So the differences of these two kinds of CHP systems are similar to the differences between coal-fired power generation unit and CCGT unit. In 2010, 89% of electrical capacity of all installed schemes are in the industrial sector and 68% of the fuel used in CHP schemes was natural gas [77]. Therefore improving energy and exergy efficiency in CHP plants is an approach to reduce the fuel demand of the industrial sector and save energy.

4.4 Summary

In the industrial sector, the energy demand for a wide range temperature requirements are normally from fuel combustion. There are two types of temperature requirements. One is the requirement of steam or hot water and the other is the requirement of high temperature environment for some reactions, melting, and drying, such as iron and steel industry, cement industry and glass industry. Tracking the energy consumption cycle for heat demand and analyzing the thermal processes in each industrial sub-sector become the main study contents of industry energy analysis in order to find available energy saving potentials and the most carbon emission reduction potentials. The next two chapters will analyze thermal processes in the electricity industry and the iron and steel industry, which are classic steam generation processes and coal consumption processes for high temperature reaction. These studies will try to find thermal efficiency increasing potentials by using the exergy method in these two industrial sub-sectors in the UK and combine state-of-the-art technology to give valuable energy saving suggestions.

5. Power generation industry in the UK

5.1 Introduction

Electricity is a high-grade energy carrier in the sense that it can be used to provide either power or heat [1]. Therefore electricity is the first option for most of the energy end-users and normally generated in advanced [1]. As the 'engine' that is driving the national economy, electricity demand tends to increase with the growth in GDP (see Table 11). According to data in Table 11, since the development of energy saving technology and competition on the energy market [24], the electricity demand increasing only 9.6% and electricity intensity reduced 14% in 2004 comparing with that in 1996, while during the same period, the ratio of energy to GDP decreased 18.7% and the proportion of net import electricity reduced from 5% in 1996 to 2% in 2004. The information displays the improvement of energy efficiency and electricity supply security. Following the reduction of electricity intensity, there was 257.3 TWh electricity being saved in the 8 years proceeding 2004 (see Table11). The energy ratio and electricity intensity have been decreasing in the past several years, however more primary fuel was used for electricity generation, both the net primary fuel inupt and the proportion of primary fuel used,(see Figure 22 & 23) in the UK. So improving energy efficiency in electricity industry is an important way to save energy in the whole energy system in th UK.

	Unit	1996	2004
Gross domestic product	£ billion	837.2	1066.5
Primary energy consumption	Million tonnes of oil equivalent	230.1	238.2
Energy ratio	Tonnes of oil equivalent per £1 million GDP	274.9	223.4
Electricity generated	TWh	350.87	395.63
Electricity used on works	TWh	16.08	17.17
Net electricity imports	TWh	16.76	7.49
Loss in transmission	TWh	29.34	32.05
Electricity supply (net)	TWh	332.36	374.96
Electricity consumption	TWh	319.78	350.40
Electricity intensity	kWhs per £1 GDP	0.382	0.329

Table 11: UK gross domestic product, primary energy consumption and electricity generation, supply and consumption (Source: DTI 2004)

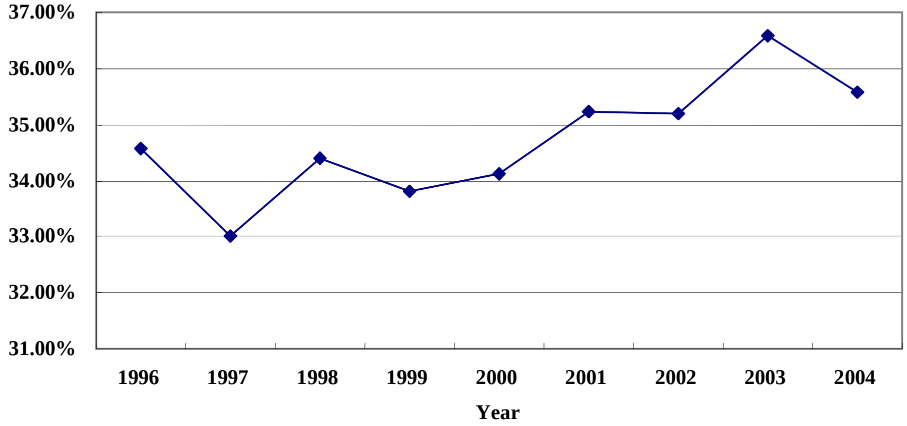


Figure 22: Fuel used for electricity generation in primary energy input in the UK from 1996 to 2004 (percentage share). (Source: DTI, 2004)

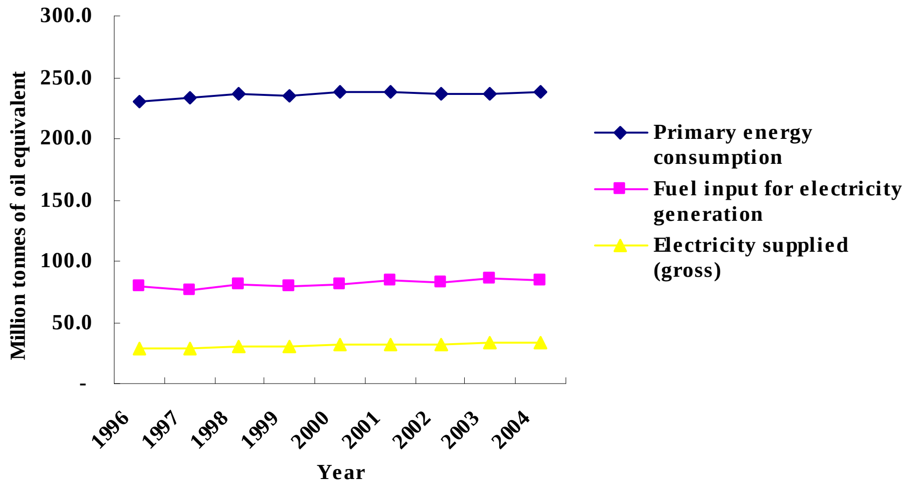


Figure 23: Primary energy consumption, fuel input for electricity generation and electricity supplied (gross) in the UK from 1996 to 2004. (Source: DTI, 2004)

Therefore, the electricity generation sector is the biggest customer of primary energy in the UK. A conventional energy resource, fossil fuel, still provides most of the primary energy market for the electricity industry in the UK (See Figure 24 &Table 12, **Source: DECC 2011, [77])**). The conventional coal-fired power plants took up 39% of power generation capacities in 2010 (**Source: DECC 2011, [77])**. The 2nd largest of the electricity supplier is CCGT power plant, which is 38% and very close to the conventional stations (**Source: DECC 2011, [77])**. Although renewable stations and hydro-electric stations play more and more important roles in today's UK electricity system, thermal power plants based on chemical fuels, including conventional steam stations, combined cycle gas turbine station and gas turbine and oil engines, still supply most of the electricity supply, which is 78.5% total installed capacity. Therefore, analyzing the energy flow during the working processes in thermal power plants, especially in convention coal-fired and CCGT power plants, improving steam conditions and equipments efficiency, controlling working substances to work at optimum parameters, and optimizing structure of electricity distribution and transmission system are the main route to saving energy in the UK power system. However, combustion fossil fuel is the biggest CO_2 emitter. Improving the power plant efficiency means less CO_2 output for the same electricity output. CO_2 capture and storage are effective technologies for reducing CO_2 emission, which are under development and some of them have been applied on a small-scale. The state-of-the-art technologies can reduce 80-95% of CO_2 in the exhaust gas of coal-fired power plant. But, considering their investment, and operational costs, as well as their power penalty, these technologies are immature and under development.

Total capacity	**80,370 MW**
Of which:	
Conventional steam stations	**35,169 MW**
Combined cycle gas turbine stations	**34,099 MW**
Gas turbines and oil engines	**1,560 MW**
Nuclear stations	**10,865MW**
Hydro-electric stations:	
Natural flow	**1,460 MW**
Pumped storage	**2,788 MW**
Wind	**2,260 MW**
Renewables other than hydro and wind	**1,960 MW**

Table 12: Electricity generation plant capacities in the UK by 2010 (Source: DECC 2011, [77])

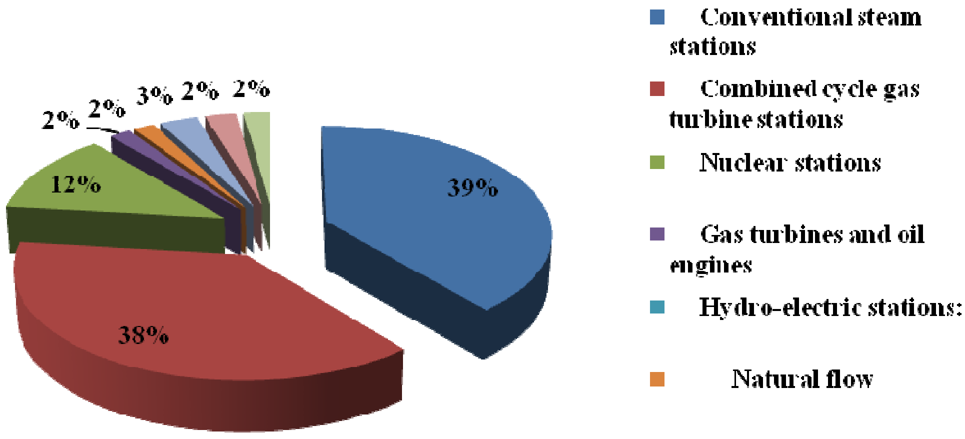


Figure 24: Components of power plant capacity in the UK by 2010 (percentage shares) (Source: DECC 2011, [77])

5.2 Energy saving and carbon emission reduction potential in the power industry in the UK

Both conventional steam stations and CCGT power plants belong to thermal power plants, which convert thermal energy into electricity by burning fossil fuel. So the thermodynamic analysis of the energy conversion processes in conventional steam stations or state-of-the-art CCGT power plants is the main effective and useful method to find out saving potential, which is adopted by many of experts and engineers. For thermodynamic analysis, Hammond and Stapleton [1] used exergy analysis to study U.K. power generation (see Table 13 [6]). The energy and exergy efficiencies are quite similar, but this hides the underlying causes for power plant exergy losses or irreversibility [6]. Actually, during the generation process in a normal coal-fired steam power plant, large losses of energy occur in the condenser, but two main irreversible processes, combustion and heat transfer, waste considerable exergy. Table 14 presented by Reistad [6] gives a detailed breakdown of the energy and exergy losses across each component of a U.S. coal-fired power station. So, if heat is required by customers, it is in theory that burning fuel directly or generating high temperature steam in industrial boiler should be far more efficient than heating by electricity because the total exergy loss of heating by electricity including the exergy loss of electricity generation is more than fuel combustion directly due to most of the electricity from thermal power plants according to DECC 2011 statistics that 96% electricity is from thermal source power stations and 75% of electricity is generated with the combustion of coal, gas and oil [77].

Considering high natural gas price, nuclear security and high cost of renewable energy technologies, coal-fired steam stations will continue to play a part in thu UK electricity supply system because of the low cost of coal and reliable technology. Most of coal-fired power stations use of pulverised fuel (PF) boilers. In these systems, coal is ground into fine particles and injected with air into a combustor. Basic supercritical PF technologies can achieve efficiencies of about 42% [36]. Advanced, "ultra-supercritical" boilers can achieve efficiencies of 45-47% [36]. Several coal combustion technologies are available today and other advanced technologies are approaching commercial viability. Supercritical PF technology can now be considered "conventional" in a number of countries. With the efficiency improvement and other advantages, supercritical technology has become a good choice for conventional coal-fired power plant, both new build and refits. Due to the improvement of steam conditions, coal combustion gives rise to higher quality thermal exergy. The result is that less steam can offer the same electricity output compared with the same size subcritical power plant. Due to the improvement of steam conditions, the plant efficiency is also improved and specific coal consumption is reduced. Currently, advanced subcritical power plant working with the steam conditions of 16.7MPa/538°C/538°C can have efficiency of 38% and consumes 0.32 kg coal per kWh electricity, while advanced supercritical power plant in Denmark can achieve the efficiency 47% with the specific coal consumption 0.26kg/kWh [36]. The reduction of coal consumption causes the decrease of CO_2 emission directly. Figure 25 shows the relationships between power plant efficiency and CO_2 emission.

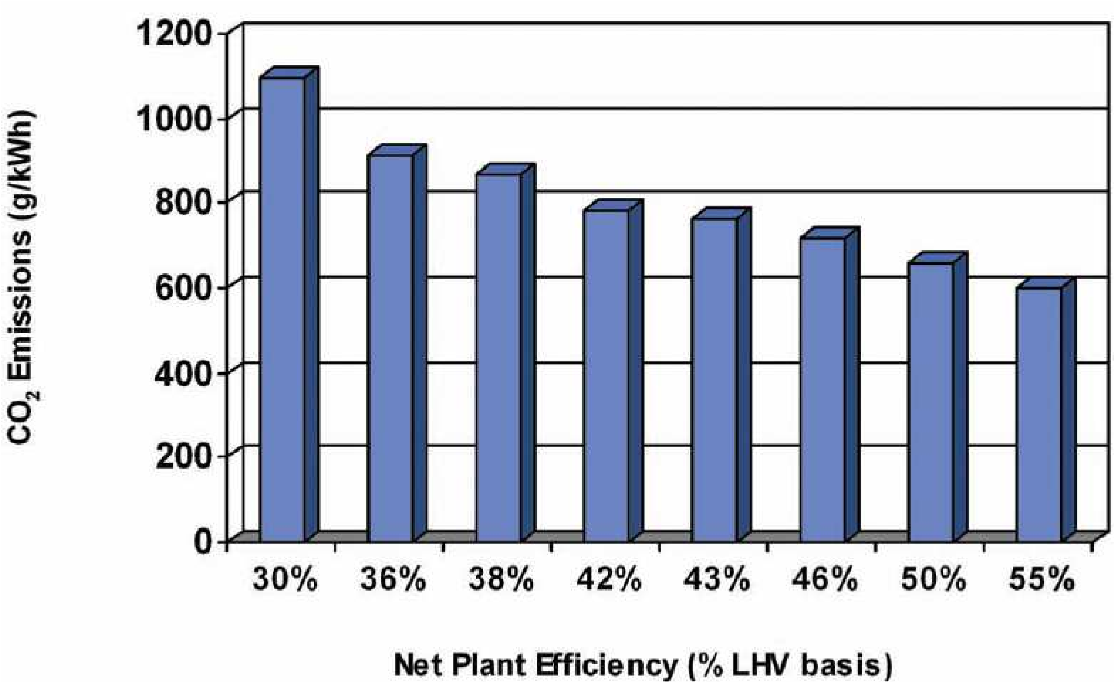


Figure 25: Decrease in CO2 emissions with increasing net plant efficiency [36]

An ultra-supercritical coal-fired power station with an efficiency of more than 50% should be possible by 2015 [36]. Further advancement in ultra-supercritical technology requires the development of advanced materials.

Power plant type	Energy-exergy relations
Conventional steam	$\psi = 0.96\eta$
CCGT	$\psi = 0.96\eta$
Nuclear	$\psi = \eta$
Hydro-electric	ψ = 78%, η= *90%*

Data source: Szargut *et al*.(1988)

Table 13: The relationship between the energy and exergy efficiencies for electricity generation [6]

Plant components	Energy losses (% of plant input)	Exergy losses (% of plant input)
Steam generator	9.0	49.0
combustion		(29.7)
heat exchanger		(14.9)
thermal stack loss		(0.6)
diffusional stack loss		(3.8)
Turbines	~0	4.0
Condenser	47.0	1.5
Heaters	~0	1.0
Miscellaneous	3.0	5.5
Plant totals	59.0	61.0
Generation efficiencies*	η=100-59=41	ψ=100-61=39

Source: Reistad [6]; U.S. conventional design.

*Efficiencies based on gross calorific or higher heating value (HHV) of fuels.

Table 14: Thermodynamic performance of coal-fired power stations

Combined heat and power (CHP) or ‘co-generation’ systems are designed for the optimum utility of energy. It is a high efficiency mode of energy generation and supply, because exhaust steam from an electricity generation system still contain considerable thermal energy. Compared with the Rankine cycle, CHP recovers most of waste heat stored in exhaust steam, improves the overall efficiency and saves fuel input. CHP system is a good heat supply type for industry, because about 40% of industrial energy is used to produce low-pressure process steam [37]. The advantages of CHP are not only shown through waste heat recovery and energy efficiency, but also reflected from exergy analysis. With the development of technology, the overall energy efficiency of CHP plant is up to 80% in the industrialized countries. In fact, all the fossil fuel ‘power’ station designs have a high CHP potential [6]. The U.K. Government currently in interested in the construction of CHP plants [6]. By the end of 2004, the total capacity of CHP system in the UK was 3102.9MWe and 2730.9MWe were good quality CHP for these sites in total. According to GB Seven Year Statement presented by National Grid, the UK will increase 560MW in CHP capacity before 2011/12. In addition to the more efficient use of fuels, CHP systems produce less air pollutants and lower thermal discharges than equivalent single-purpose systems [37].

By 2010, combined cycle gas turbine (CCGT) power plants had taken up 38% of all installed capacity in the UK, achieved 34,099 MW (see Table 12 &Figure 24). CCGT system offers high efficiency combined with the low carbon content of natural gas [38] and utilizes the exhaust heat of gas turbine in term of heat recovery steam generator (HRSG) technology. Therefore CCGT power plants have higher thermal efficiency than any single-cycle thermal power plants with far lower CO2 emission and other air pollutants. According to Tauschitz and Hochfellner’s research on a new 800 MW combined cycle power plant of ATP in south of Graz, the efficiency of CCGT increases with the growth of unit size and load (see Fig 26 &27 [39]).

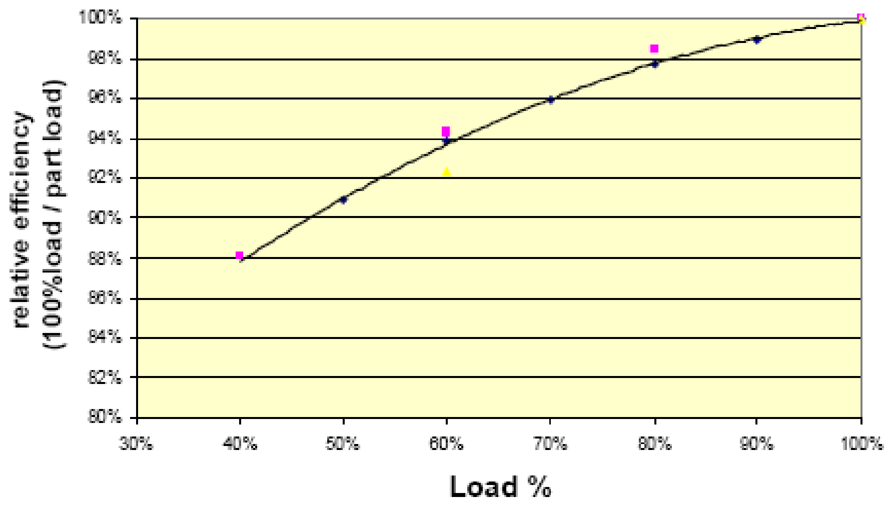


Figure 26: Influence of load factor to the CCGT efficiency [39]

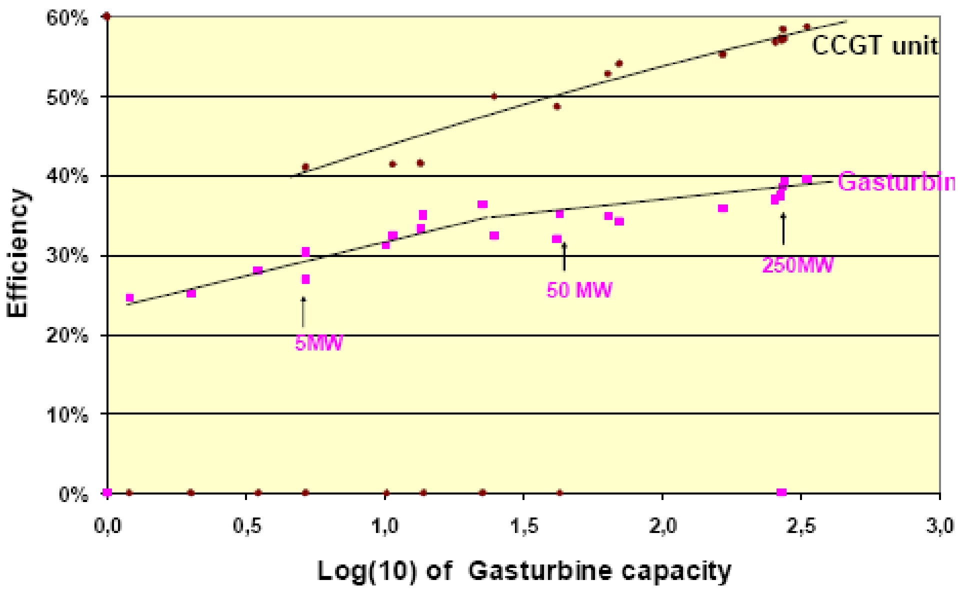


Figure 27: Efficiency of gas turbines and CCGT units [39]

The efficiency of large-scale CCGT station can achieve about 58% at full-load, but at 50% load, the efficiency would decrease 10%. So, a large size CCGT unit is the best option to meet the basic load requirements and not fit for peak load. If electricity is not in great demand, switching off some units and keeping others working at full-load can obtain higher efficiency than letting most of unites work at partial load. Moreover, CCGT would reduce CO_2 emissions and other air pollutants dramatically, comparing with coal-fired power station by burning natural gas. Table 15 shows the difference of CO_2 emissions between CCGT and other coal-fired power stations, even in ultra-supercritical coal-fired power plant, CO_2 emission for per kWh electricity output is still far more than the double of that in natural gas GGCT station. By the end of 2010, there were 34,099 MW installed CCGT units in the UK, but the load factor of CCGT plants was 60.6%, less than 84.0% in 1999. So if the load factor of CCGT is improved one percent to cover the electricity generated by coal-fired stations, according to the installed capacity in 2010, about 6,453 GJ per year energy can be saved and CO_2 emissions would reduce 1797 tonnes per year. Due to the huge potential of energy saving and carbon reduction, more CCGT stations have been installed in the last 10 years to replace more conventional coal-fired steam stations (see Figure 28 & 29). From 1996 to 2010, the installed capacity of conventional steam stations reduced 15% from 41459MW in 1996 to 35196MW in 2010 and during the same period, the capacity of installed CCGT stations in 2010 was 2.7 times as much as that in 1996 (Source: DECC 2011,

[77]). The trends shown in Figure 28 & 29 reflect the potential of energy saving and CO_2 emission reduction by replacing conventional steam stations with CCGT stations. In the coming years, more CCGT plant will take up more electricity market in the UK. Furthermore, combining CCGT system with district heating can hold the advantages of CCGT and CHP and build a kind of energy supply mode with high thermal efficiency and low pollutants emission.

Power Plant	**Emissions CO2 g/kWh**
Conventional coal	900
Supercritical coal	800
Ultra-supercritical coal	750
Natural gas CCGT	300

Table 15: CO_2 emissions from fossil fuel plant [41]

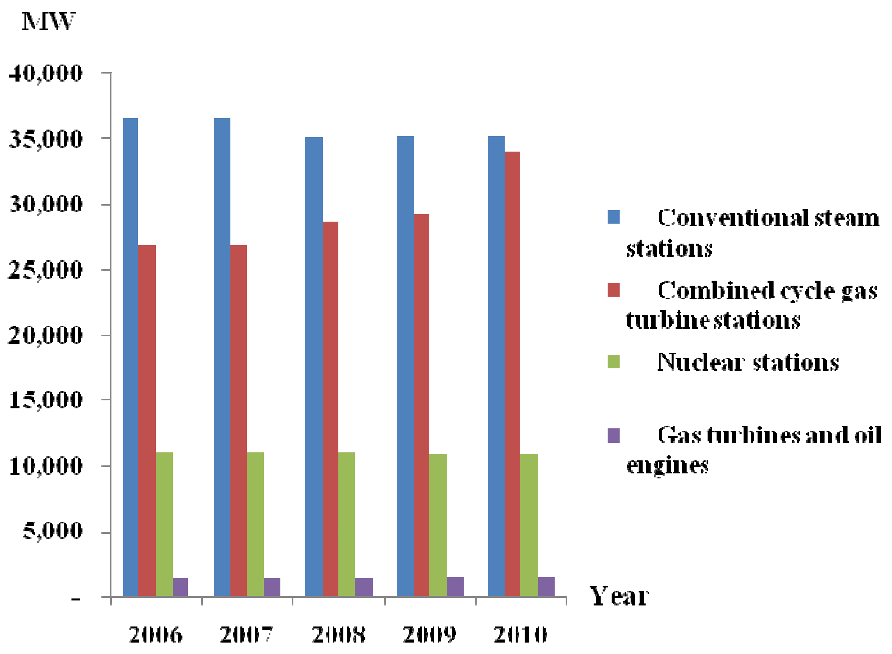


Figure 28: U.K. electricity generation by coal-fired stations, CCGT plants and nuclear stations (Source: DECC 2011, [77])

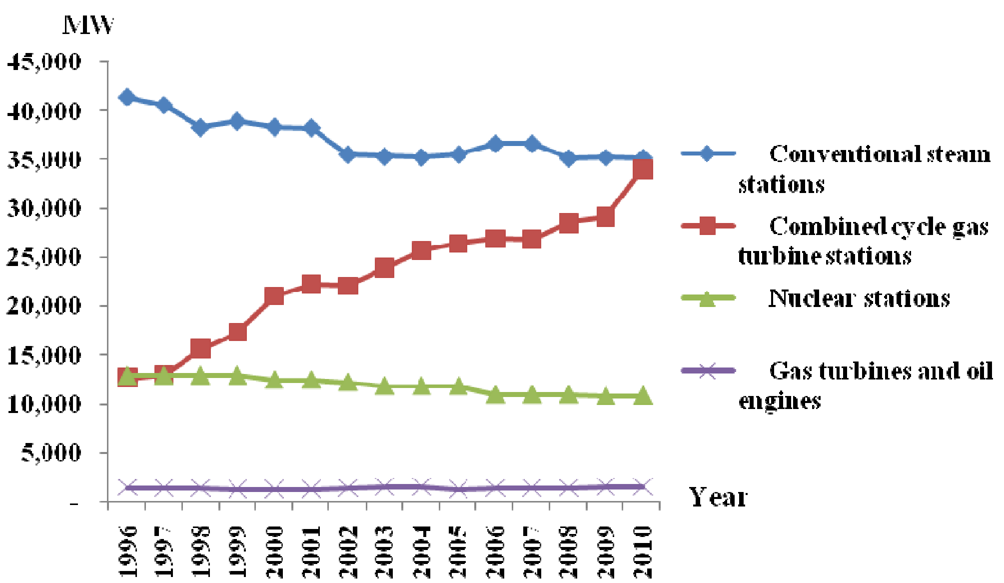


Figure 29: Installed capacity of conventional steam stations, CCGT stations and nuclear stations from 1996 to 2010 (Source: DECC 2011, [77])

5.3 Summary

In industrialized countries, electricity has become a necessary resource for society, like food and water. Electricity underpins a modern country. Without electricity, all factories have to stop running, no water supply, and no gas supply, because these systems are driven by electricity.

According to the trend of the development of power generation technology, in the next several decades, it is difficult to find some energy carrier to replace electricity. Therefore, the target of reduction of the carbon emissions from power generation industry has to depend on increasing the proportion of loe or zero carbon electricity, such as nuclear power, hydroelectric power, wind power and other renewable energy. Considering the capacity of wind power and the geographical limitation of hydroelectric power, nuclear power becomes the first choice of UK power generation without CO_2 emission. The main problems for nuclear power are nuclear safety and nuclear waste treatment. Hammond [42] reviewed the development of nuclear power. Currently, UK, China and U.S. have all announced their new nuclear power plan to face the possible energy shortage. They are attractive because of the high price of petroleum and natural gas, and the high carbon content is coal-fired power generation. According to the discussion above, supercritical and ultra-supercritical power plants will be the main choices for new coal-fired build power plant. Moreover, the development of CCS technology makes it possible to reduce most of the CO_2 emission from coal-fired power plants. If there are some relevant policies or regulations being made to manage, encourage and finance the carbon separation in power plant, the CO_2 emission from coal-fired power plant can get effectively controlled.

6. Energy consumption in iron and steel industry in the UK

6.1 Introduction

Since most of the production processes in iron and steel industry requires high working temperature, like coke making, iron production, crude steel production and steel casting shaping, the iron and steel industry is the traditional energy-intensity industry due to large amount energy use for process heating. Although science and technology have improved dramatically, the basic theory and making processes of iron and steel industry are still that of reducing iron from iron ore by coke. High temperatures are necessary to achieve several goals, e.g. to change the structure of ores and coal so that they can be processed in the blast furnace, to overcome kinetic and thermodynamic constraint to chemical reactions in the reduction of iron oxide, and to provide steel in a liquid form so that it can be shaped [8]. This chapter would analysis the energy and exergy consumption status in today's UK iron and steel industry, especial the exergy flow in high temperature working processes, and then find the energy saving potential with the application of the latest iron and steel making technologies.

6.2 Iron and steel generation processes in the UK

Steel industry is a conventional energy intensive industry. According to SIC2003, 10 sub-sectors are associated with iron and steel industry in the UK (see Table 16). In the SIC 2003 system, coke industry is excluded in steel industry. Actually 97% of the demand for coke oven coke was at blast furnaces and around 95% of coke oven coke and coke breeze is home produced in 2009 [70], the energy consumption and transmission in coke oven would be taken into account as a content of energy analysis in UK's iron and steel industry. Moreover, 85% of coking coal was mainly used in coke ovens for 95% coke and coke breeze supply and the rest 15% was also used in steel industry and directly injected into blast furnaces in 2009 [70]. Hence, the coke manufacture is classified in steel industry by ISSB and the energy consumption in coke oven would be analysis in this study. Coal combustion process is also the main carbon emission resource, the energy analysis of coke oven can contribute for both energy saving and carbon emission reduction.

Thousand tonnes of oil equivalent		
SIC(2003) codes	**Description**	**Energy consumption**
2710	Manufacture of basic iron and steel and of ferro-alloys (ECSC)	1530
2721	Manufacture of cast iron tubes	19
2722	Manufacture of steel tubes	57
2731	Cold drawing	4
2732	Cold rolling of narrow strip	5
2733	Cold forming or folding	2
2734	Wire drawing	11
2745	Other non-ferrous metal production	-
2751	Casting of iron	45
2752	Casting of steel	24
	Total	1697

Table 16: Energy consumption by all sub-sectors of steel industry in 2007, excluding for making coke (Source: DECC 2011, [77])

The iron and steel industry can be divided into to two sections: crude steel production and steel products making. As shown in Table 16, crude steel production, SIC2710， Manufacture of basic iron and steel and of ferro-alloys (ECSC), consumed 90% of the energy in this catalog (see Table 16). So the energy consumption for iron and steel production directly determines energy intensity of the iron and steel industry in UK.

Open hearth furnaces have been closed in 1970s; there are only two crude production methods in today's UK steel industry, producing crude steel from blast furnace and basic oxygen steel furnace (BF-BOF) and producing crude steel via electric furnace.

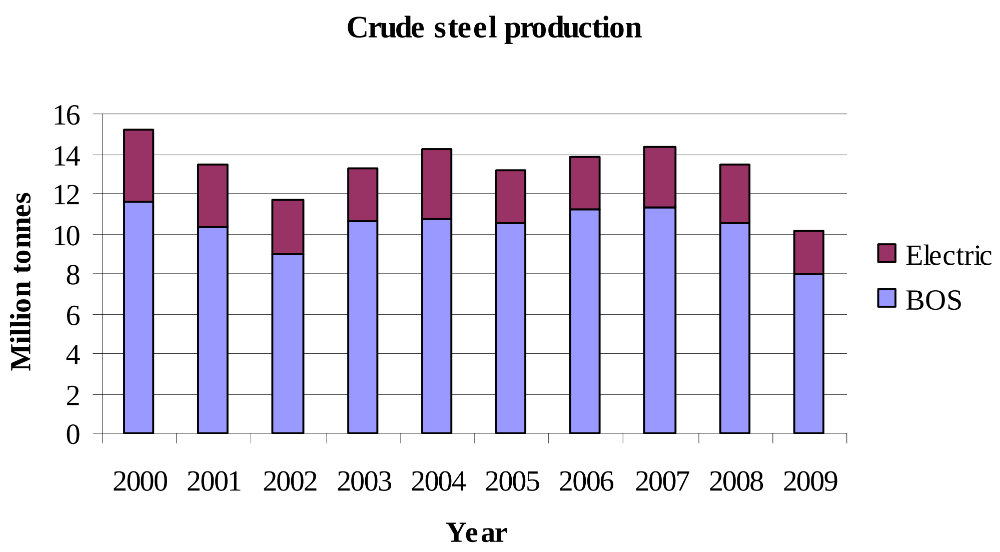


Figure 30: Crude steel production from 2000 to 2009 in UK. (Data source: ISSB website [81])

Since the drop in the demand for steel in the recent years, the home produced crude steel has tended to fall with some wave in some years in the latest decade (see Figure 30) [81]. Moreover, the crude steel made from electric furnace has reduced a lot neither for the production nor for the proportion in whole crude steel production from 2000 (see Figure 30, 31) [81].

Since the BOS steel works offer most of the crude steel supply in UK and the steel producing process in BF-BOS is completed and high energy intensive, the following study would pay more attention to the energy consumption in integrated steel plant.

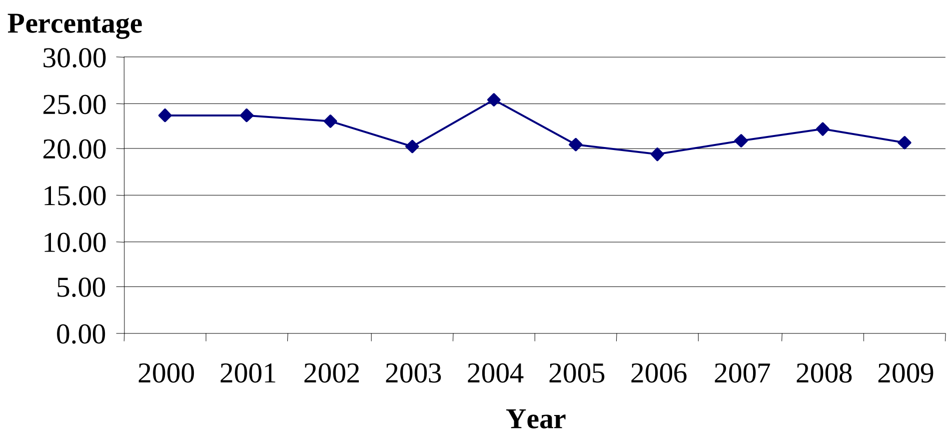


Figure 31: Percentage of crude steel production from electric furnace from 2000 to 2009 in UK (data source: ISSB website [81])

Figure 32 is the principle process and the energy and material flow in UK integrated plant. In Figure 32, the black line shows the material flows and energy flow is shown with the red line. The energy flow includes not only practical energy input, like coke, electricity, but also energy going into the system with material flow in the form of thermal power, such as the sensible heat in melt pig iron.

The following study would analyze the energy consumption status in recent years and point out the main energy saving potentials according to the exergy analysis results and the state-of-the-art technologies for steel production.

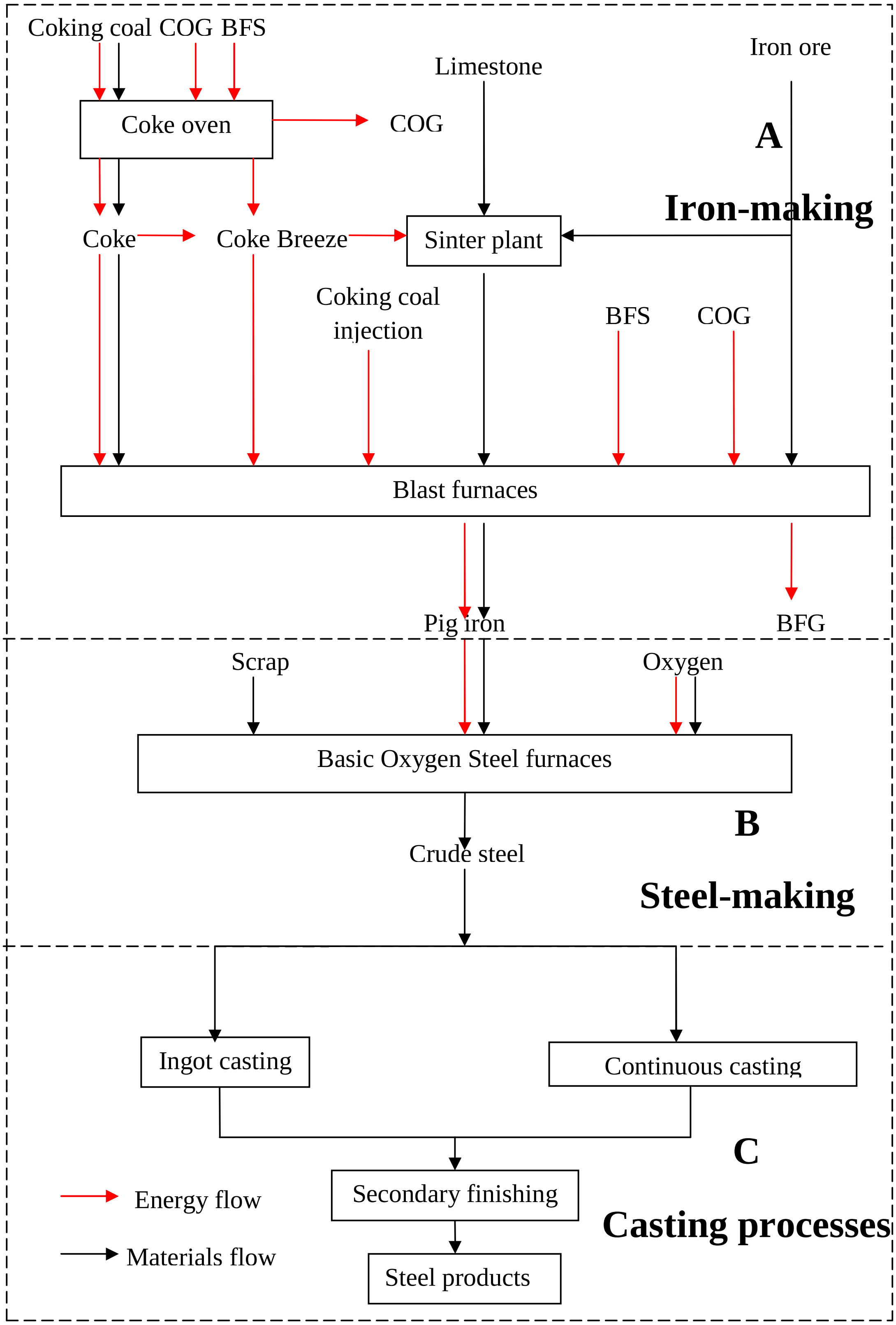


Figure 32: Principal energy and material flows of the integrated steel plant in UK.

6.3 Energy and exergy analysis of the iron and steel industry in the UK

In the digest of United Kingdom Energy Statistics 2010 coal consumed in coke oven coke and blast furnace and coke consumption in blast furnace are classified into the category of transformation in commodity balances. Considering that coal and coke's energy contribution, their energy supply function would be studied here. Base on the data in DUKES 2011 [77], net energy consumption for crude steel production in the integrated steel plants is 16.56 GJ per tonne crude steel including energy consumption in the coke oven.

The Main energy loss happens in the coke ovens and blast furnaces, because of large quantity fuel combustion for high temperature requirement. However, energy flow cannot reflect the energy consumption mechanism clearly and it is difficult to explain how the energy loss happens and whether it can be avoided. A theoretic exergy flow model based on the energy consumption data in 2009 UK steel industry would be built in order to find the compositions of energy loss. And then the state-of-the arts energy saving technologies would be introduced to giving the possible energy saving potentials comparing with current energy consumption status in the UK steel industry.

6.3.1 Coke making

In integrated steel plant, coke plays a very important role. It is the main raw material supplying carbon as a reduction agent to deoxidize Fe from iron oxide through chemical reactions in blast furnace. Besides working as reduction agent, coke works as main fuel in blast furnaces to keep a high temperature environment for the iron ore reduction.

Coke making is an energy intensive fuel manufacturing process (SIC 2310). It is a typical energy transformation process. "**In 2009, round 95% of coke oven coke and coke breeze is home**

produced with the rest imported. 97% of the demand for coke oven coke was at blast furnaces (part of the transformation sector) with most of the remainder going into final consumption." [71]

During the coking process, coking coals are heated to 1100℃ in the coke oven without oxygen, and then they smelt, devolatilize and re-solidify to form coke [12]. Because of the high temperature in the coke oven, the useless components for iron making in the coal can be reduced. Most of the hydrogen, oxygen, nitrogen, sulphur and other volatile components in the coal are released in such a high temperature environment and form coke oven gas (calorific value ~20MJ/Nm^3 [11]), which is the main by-product of coke making.

Energy input		GJ/tonne coke
	Coking coal	43.93
	COG	3.85
	BFG	0.51
	Electricity	0.99
	Total	49.27
Energy output		
	Coke	29.80
	Coke breeze	0.20
	COG	7.87
	Benzole and tars	1.51
	Total	39.38
Energy loss		9.89

Table17: Energy consumption for coke production in UK in 2009, (data source: [70])

Table 17 gives the energy consumption details in UK coke manufacturers. The energy loss per tonne coke is 9.89 GJ, which is also the energy consumed for per tonne coke production. It must be noticed that 0.99GJ electricity are mainly used for mechanical power requirement and light demand in coke production, so the electricity actually is not the part of energy transmission in coke oven. So the thermal energy loss in coke oven due to thermal process is 8.9 GJ per tonne coke. However, the energy analysis cannot reflect where and what the energy is used for. So exergy analysis is applied to find the details of the 8.9 GJ energy losses. Most of the energy loss in coking process is the sensible heat with COG and coke rejected to environment and the heat rejected to environment from equipment surfaces.

Exergy analysis			
Input			**GJ/tonne coke**
	Coking coal		**43.93**
	COG		**3.85**
	BFG		**0.51**
	Electricity		**0.99**
	Total		**49.27**
Output			
	Coke		**29.8**
	Coke breeze		**0.20**
	COG		**7.87**
	Benzole and tars		**1.51**
	Total		**39.38**
Difference (Loss)			
	Total exergy of sensible heat		**2.11**
		Coke at 1100°C	**1.64**
		Coke breeze	**0.01**
		COG （1100°C—700°C）	**0.17**
		COG （700°C—10°C）	**0.29**
	Other		**7.79**

Table 18: Exergy analysis of coke making in UK in 2009 (data source: [70])

Since the relationship between fuels chemical exergy and their net heat values shown in Table 3 & 4, for the convenient of calculation and analysis, the net heat values of the fuels are also considered as the fuels chemical exergy directly. Table 18 compares the exergy values of the inputs and outputs. In coke oven, the temperature is 1100°C and 10°C is the ambient temperature applied here for exergy analysis. Due to the high working temperature, the outputs contain high sensible heat. Table 18 gives the details of the main sensible heat, which are also the main thermal exergy outputs. The sensible heat is theoretic recyclable thermal exergy. Besides the sensible heat, the other part of the exergy loss is due to combustion and heat transfer to the environment, in which combustion contributes most of the exergy loss. Because the processes that happen in the coke oven are energy transmission processes and all inputs and outputs are energy products, the energy and exergy inputs and outputs are similar. The main energy loss is also the same as the big exergy loss in quantity.

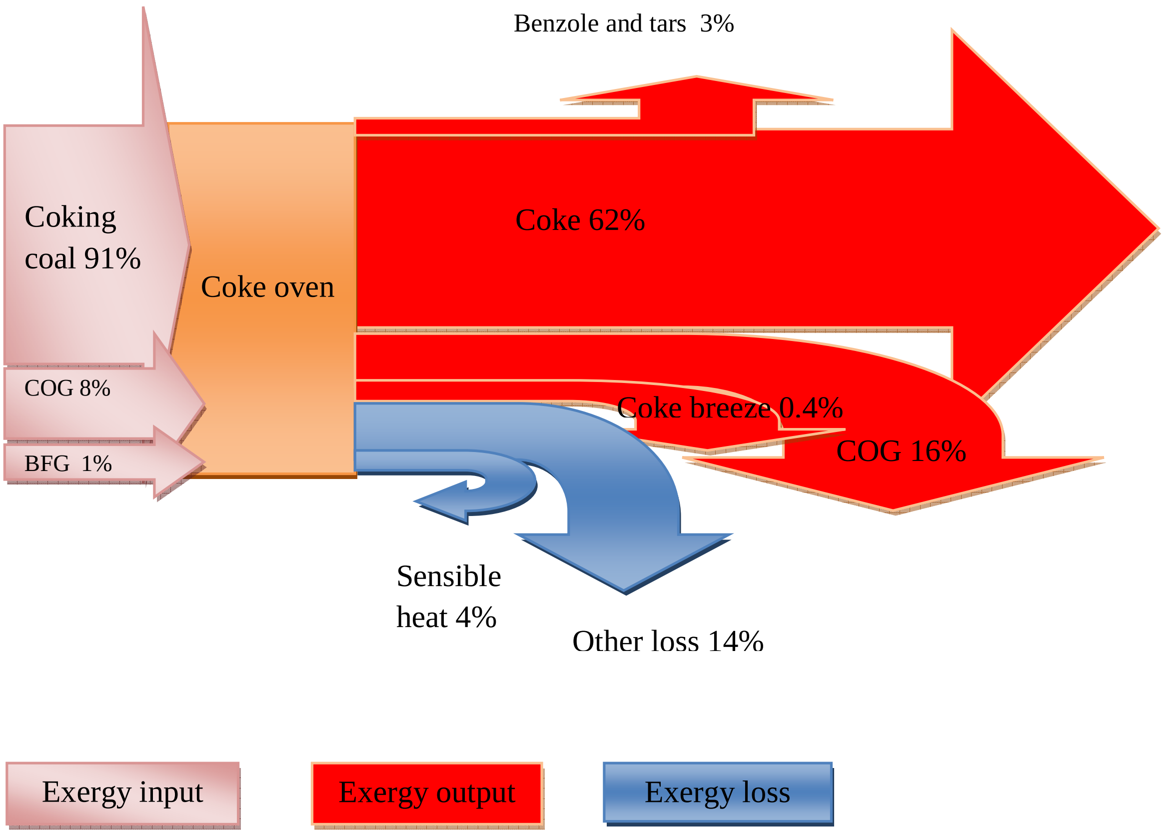


Figure 33: Exergy diagram of coke making process in UK in 2009 (data source: [70])

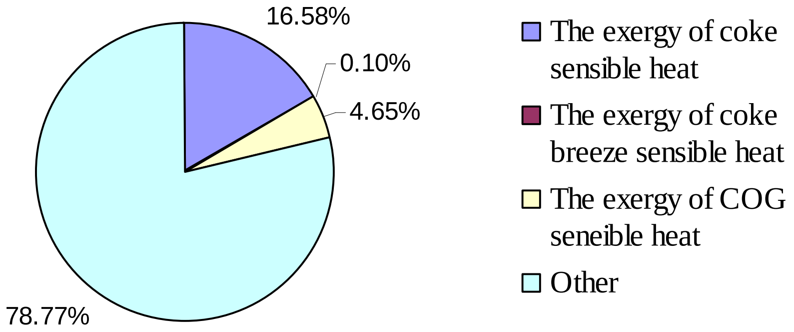


Figure 34: Exergy loss compositions during coke making (data source: [70])

In modern coke plants, the COG is the main by-product, which is normally collected and used as fuel for electricity and steam generation, combustion in the sinter plant and other fuel needed places. The largest single loss is the sensible heat in the incandescent coke [11]. The temperature of the incandescent coke is about 1100℃ and the thermal exergy of incandescent coke is about 1.64GJ per tonne of coke, so it becomes the main thermal exergy loss. Traditional wet coke quenching uses cold water to cool incandescent coke and wastes. The sensible heat of COG is 0.46GJ per tonne coke, which is the second largest thermal energy in all outputs of coke oven. The temperature of COG leaving coke oven is normally at 700℃ with thermal exergy 0.29GJ per tonne coke, which is normally used for coal preheating, production of steam and hot water. But actually the temperature of COG in the centre of the coke oven is about 1100℃. The thermal exergy from 1100℃ to 700℃ is about 0.17GJ per tonne coke. The sensible heat of COG at 1100℃ and the sensible heat of incandescent coke are the biggest saving potential of thermal energy in coke making process. Besides the sensible heat of incandescent coke and COG, the sensible heat of combustion exhaust gas and other waste heat can be recovered to preheat combustion air and fuel gas mixture [13] and meet other demands of low temperature heat, such as space heat.

Considering the characteristics of combustion and the high temperature of combustion in coke oven, both COG side and coal side, preheating COG, combustion air and coal by recycled sensible heat ant waste heat is an effective method to reduce the exergy loss of combustion.

Currently, the recovery and utilization of COG is widely adopted, but it is to use the chemical energy in COG and a large quantity of sensible heat going out coke oven with COG is difficult to be recovered. Considering the high efficiency of CHP system and the large production of COG in coke plant, using the hot COG to driving CCTG system can transfer the thermal energy and chemical energy in COG to electricity and hot products, steam of hot water, which are easily collected, transported and used. Moreover, other sensible heat with waste and coke can also be recovered to heat the air for the demand of CCGT system.

However, the target of steel industry is to get steel products but not coke. Finding new low energy cost reduction agent to take the place of coke iron production is the more efficient way to reduce energy demand than recovering sensible heat in coke plant.

6.3.2 Sinter plant

About three quarters of iron used in a blast furnace producing pig iron for steel making is charged in the form of sinter, rather than directly as ore [11]. During the sinter production process, the energy inputs are coke breeze and COG and the main energy conversion process is the combustion of coke breeze at about 1300℃—1400℃. Because of the lack of detailed statistics about sinter making in the British steel industry, it is difficult to identify most of the energy saving potential in the sinter making process. However, due to the high temperature of roasting in the sinter making process, the sensible heat of hot sinter and off-gas contains a large amount of thermal exergy, which includes the main energy saving potential during the sinter making process. For example, the hot sinter can be cooled by air, and then the thermal exergy would be transferred into air. Using the preheated air for combustion can improve the temperature of combustion and reduce the exergy loss of combustion, while saving COG [13].

6.3.3 Crude steel making in integrated steel plant in UK

In the last decade, over 75% of crude steel was produced from basic oxygen furnace using pig iron made by blast furnace. Integrated steel plant still supplies most of the crude steel to meet the demand of UK steel industry. There are two main steps for crude steel production in integrated steel plant, pig iron production in blast furnace and crude steel production in basic oxygen furnace.

Pig iron production process in the blast furnace consumes most of the primary energy in iron and steel industry due to high reaction temperature demand. In the blast furnace, coke combines with oxygen to form carbon monoxide [13], and then deoxidizes Fe from iron oxide through a series of reactions at high temperatures in a blast furnace [16]. The main reactions are as follow [16]:

$2Fe_2O_3 + 3C = 4Fe + 3CO_2$ ⊿G=0.5GJ/ tonne of Fe

$3Fe_2O_3 + CO = 2Fe_3O_4 + CO_2$ 150－600℃

$CO_2 = C + CO_2$

$Fe_3O_4 + CO = 3FeO + CO_2$ 600－1000℃

$FeO + CO = Fe + CO_2$

$FeO + C = Fe + CO$ 1000－1400℃

$CO_2 + C = 2CO$

$C+O_2=2CO_2$ 1400－2000℃

$2C+O_2=2CO$

In order to create a high temperature environment in a blast furnace and support enough energy to meet the demand of these reactions, a large amount of coke is used as fuel to produce heat.

Pig iron making in blast furnace is a complicated chemical and physical process and some energy is applied for chemical reaction and some chemical reactions release some energy, which are all displayed above. So the traditional energy analysis is difficult to reflect the energy changes and consumption in blast furnace clearly.

Because of technology development, the coke consumption fell down from 0.58 tonne per tonne iron in 1981 to 0.40 tonne coke and coke breeze per tonne iron with 0.11 tonne coking coal injection in 2009. Table 19 shows the coke consumption changes in main British blast furnaces between 1996 and 2009. Table 20 & 21 are the main inputs and outputs of energy and exergy analysis in UK steel industry in 2009. Besides these molten steel, approximately 27% of exergy is carried out in form of chemical exergy by blast furnace gas (BFG, here including BOF gas), which is the main energy by-product having calorific value about $3.2MJ/Nm^3$ [48]. The thermal exergy value (thermal exergy) of BFG is not high, 84MJ per tonne hot metal and the temperature of it is about 1400℃.

Energy consumption in UK blast furnace	Coke and coke breeze GJ /tonne iron	Coking coal GJ/tonne iron	BFG, COG and Natural gas GJ/tonne iron	Total GJ/tonne iron
Redcar (1996)	11.92		5.57	17.49
Scunthorpe (1996)	11.32	4.73	6.57	22.62
Wales (1996)	12.81		6.13	18.94
2009	11.85	3.47	1.91	17.23

Table 19: Energy consumption in main blast furnaces of British Steel Corporation in 1996 and average energy consumption in blast furnace in UK steel industry in 2009 (data source: [60] & [70])

Exergy input in blast furnace	Exergy(GJ) per tonne of melt steel
Coke	10.26
Coke breeze	1.59
Coking coal	3.45
Natural gas	0.20
COG	0.26
BFG	1.44
Electricity	0.21
Sinter	0.79
Iron ore	0.57[88]
Exergy input in basic oxygen furnace	**Exergy(GJ) per tone of melt steel**
	0.4 [59]
Total exergy input for steel production	**Exergy(GJ) per tone of melt steel**
	19.17
Exergy output	**Exergy(GJ) per tone of melt steel**
$Steel_{ch}$	7.1 [86]
BFG_{ch}	5.11
Total exergy output from steel production	**Exergy(GJ) per tone of melt steel**
	12.21
Total exergy loss	**Exergy(GJ) per tone of melt steel**
	6.96

Table 20: Exergy analysis of steel production in UK in 2009 (data source: ISSB website, [48], [70], [71])

Energy input in blast furnace	**Energy(GJ) per tonne of melt steel**
Coke	10.26
Coke breeze	1.59
Coking coal	3.45
Natural gas	0.20
COG	0.26
BFG	1.44
Electricity	0.21
Sinter	0.79
Energy input in basic oxygen furnace	**Energy(GJ) per tone of melt steel**
	0.4 [59]
Total energy input for steel production	**Energy(GJ) per tone of melt steel**
	18.6
Energy output	**Energy(GJ) per tone of melt steel**
BFG_{ch}	5.11
Total energy output from steel production	**Exnrgy(GJ) per tone of melt steel**
	5.11
Total energy loss	**Energy(GJ) per tone of melt steel**
	13.49

Table 21: Energy analysis of steel production in UK in 2009 (data source: ISSB website, [48], [70], [71])

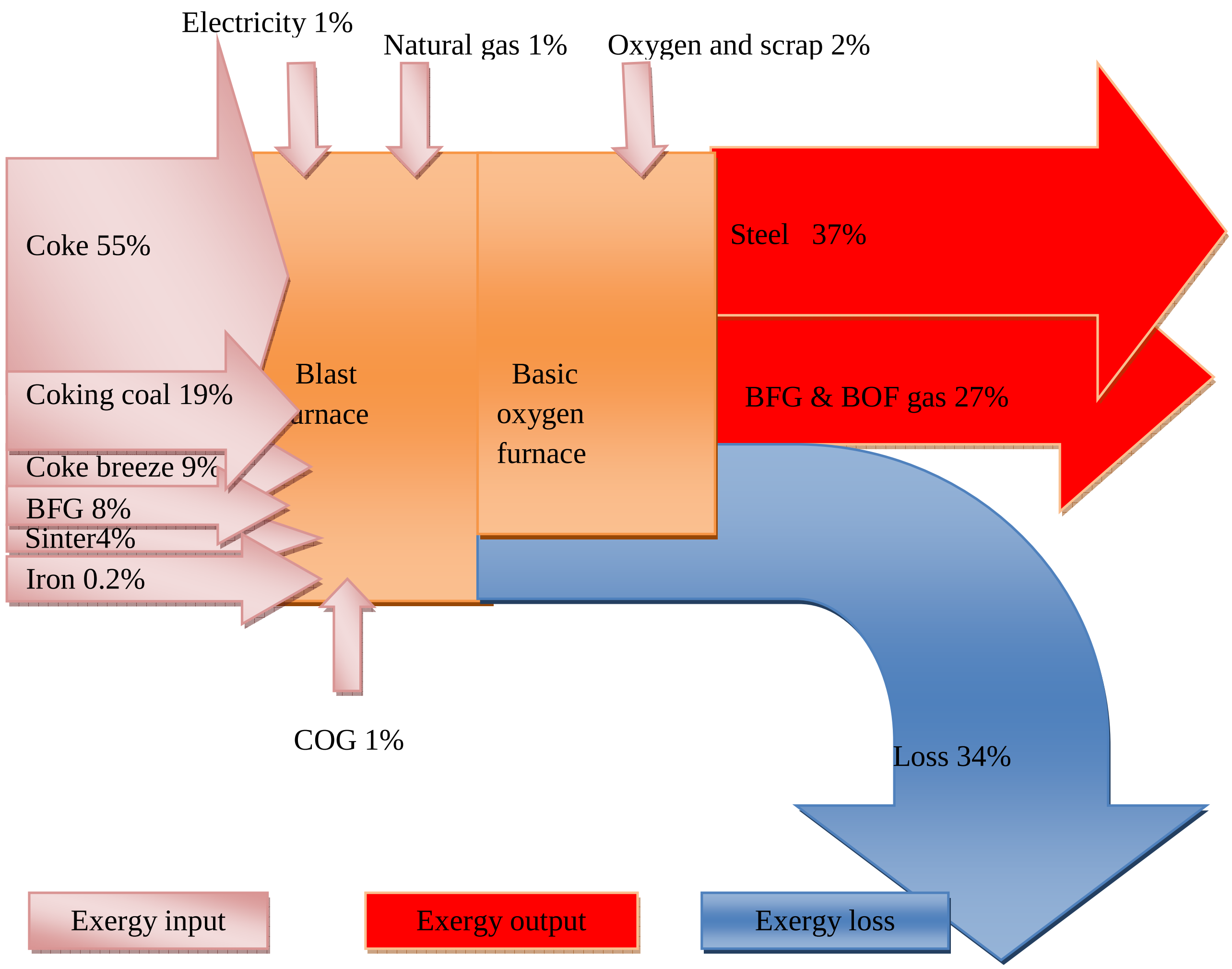


Figure 35: Exergy diagram of pig iron making in UK in 2009 (data source: [70])

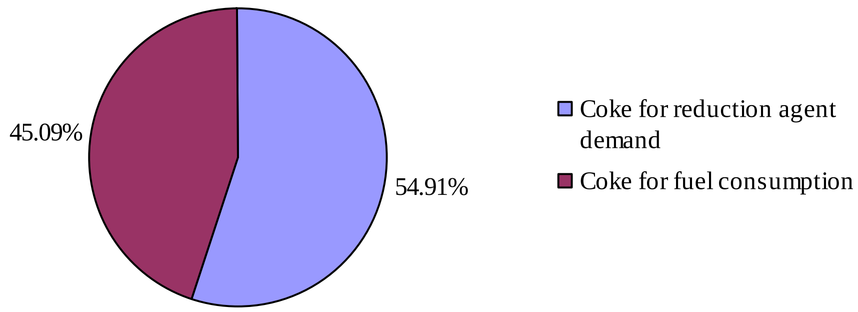


Figure 36: Theory exergy saving potential for iron making

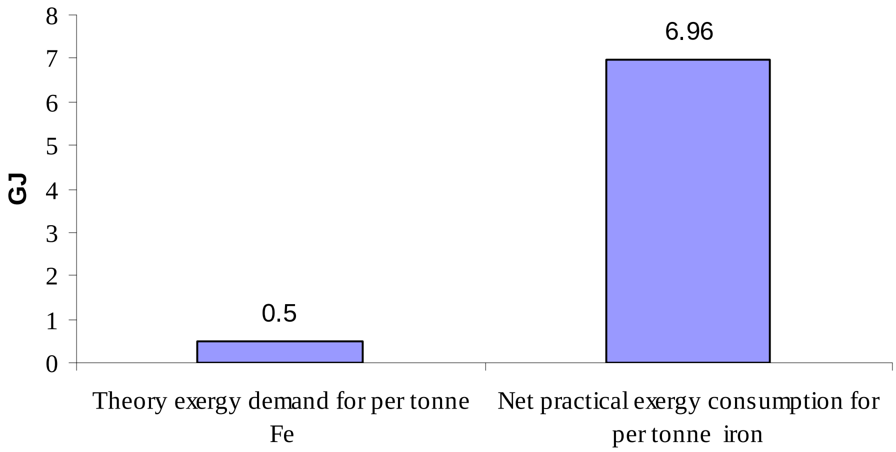


Figure 37: Theory exergy saving potential for iron making

The molten pig iron from a blast furnace would be transferred into basic oxygen furnace by torpedoes, a kind of special insulated wagon. So the energy loss due to the temperature drop during the transportation of molten pig iron cannot be particularly avoided. Normally the temperature drop from blast furnace to the basic oxygen furnace is about 120—150℃ [48]. Since the temperature of molten iron is 1500℃, the 120—150℃ temperature drop is a significant loss of thermal exergy. Minimizing these losses is very important for saving energy in the basic oxygen furnace, because the sensible heat of molten iron is the main heat resource of basic oxygen furnace. Table 20 shows the main items of exergy in basic oxygen furnace.

According to the reduction reactions happening in the blast furnace [52], it is in theory that 0.16 tonnes pure carbon is consumed as reduction agent to produce one tonne Fe which is in form of iron and this reduction process needs 0.5 GJ exergy in theory. Considering the carbon in coke is about 80-95% [72], here it takes 85% as the percentage of carbon in coke to assess theoretic coke consumption. So the theoretic coke demand for reduction agent is 0.19 tonnes per tonne steel, which is 55% of total coke consumption in blast furnace (see Figure 36), and the rest 45% coke is used as fuel. However net exergy demand of the reaction is only 0.5 GJ per tonne steel and the total exergy loss is 6.96 GJ per tonne steel (see Figure 37 & Table 20), it is very clear that 6.46 GJ is the theoretic exergy saving potential, which is actually consumed for combustion, internal heat transfer, and goes out in the form of sensible heat with all outputs. Considering energy price increasing, coke is much cheaper than other reduction agents and fuels, coke will go on serving the iron industry as the main reduction agent and fuel. Since it is difficult to reduce the coke demand for the reduction agent, reducing coke consumption as fuel is another way to reduce energy input. Improving combustion efficiency and use alternative fuels are currently widely used methods. Recovering high temperature BFG to mix with cold air and than blasting into the furnace can use both chemical exergy and sensible heat in BFG, and improve air temperature in order to modify combustion efficiency. Moreover it would not increase the fuel cost because BFG is the by-products of blast furnace. Coal injection is a widely used technology in iron making process. Coking coal normally contains around 70% carbon, which can be used as both fuel and reduction agent in theory. Moreover, using coke coal can reduce coke demand and reduce energy consumption during coking process. Considering there is lots of impurity containing in coal that would influence the effect of the reduction reaction, there should be enough coke serving as reduction agent. However, too much coal injected into the blast furnace would reduce the combustion temperature, which is not good for iron production. Modifying the combustion technology to improve the amount of coking coal being injected is a important direction for energy saving in iron production process.

An off-gas of basic oxygen furnace has a heating value of 8.0 MJ/Nm^3 [48] and a temperature of 1200℃ [19] and takes 7.4% exergy output. In modern steel manufacturers, recovering hot BOF-gas is an important measure of saving energy. The techniques of BOF-gas recovery in Japan is at the leading position in the world. A closed off-gas system has been developed by the Nippon Steel Corporation. This system can save 0.98GJ per tonne of crude steel and increase 0.4% steel production [20]. Because the output of BOF-gas per tonne of crude steel is quite smaller than the COG and BFG, the BOF-gas was not recovered before in the UK. From the end of 1980s, some projects related BOF-gas recoveries have been undertaken at Scunthorpe [73]. However, current techniques focus on the recovery and utilization the chemical exergy of BOF-gas and recovery the sensible heat in BOF Gas at low temperature because at the outlet of basic oxygen converter, the temperature of BOF-gas is as high as 1300℃ and difficult to be recovered. In recent years, a new technique transfers the sensible heat of BOF-gas in the Phase Change Material (PCM) of copper in the form of latent heat at the outlet of basic oxygen converter, and then utilizes the endothermic reaction between COG and steam to store these thermal exergy in methanol as chemical exergy [74]. Comparing with thermal exergy, the chemical exergy is a kind of stable form and more difficult to degrade. So the sensible heat of BOF-gas can be taken out and used to produce methanol. This technique not only recovers the high thermal exergy of BOF-gas and also reduces the energy consumption in methanol production, because the exergy loss due to combustion and steam generation is avoided. So the exergy consumption for methanol production by this method is only 28% of conventional method [74].

Besides the heating value and thermal exergy of BOF-gas, the sensible heat of incandescence BOF-slag is another important energy saving potential, amounting to 0.14 GJ per tonne of crude steel [73].

6.3.5 Finishing operations

The processing of crude steel into the finished products sold by the steel industries involves two distinct stages: primary finishing and secondary finishing [48]. The energy consumption during the whole finishing processes shared 9.8% of all steel industry energy consumption (see Table 16).

During the first stage, casting is the main operation of primary finishing. With the advantages of the energy saving and the low loss of metal compared with ingot casting, the BSC keeps improving the proportion of continuous casting in the primary finishing stage, and by the end of 2005, 97.8% of the crude steel was casted continuously. In the UK, the energy consumption in continuous casting process is a small input of fuel and electricity, amounting to 0.18 GJ per tonne crude steel [48].

After casting, the semi-finished steel would be reheated and rolled to form the final products, and then cooled in cooling banks [48]. The energy requirement in secondary finishing is estimated to be 2.8 GJ per tonne of semi-finished steel, equaling to 2.5 GJ per tonne of crude steel [48].

6.4 Energy saving potential in the iron and steel industry in UK

For any energy saving project, reducing energy demand and recovering waste energy, mainly waste heat, are the two major aspects. It is same for the steel and iron industry. There are two main factors causing the high energy consumption in the iron and steel industry, coke consumption for iron reduction in blast furnace and high temperature requirement in every production process. Coke consumption for iron reduction is determined by the forms of iron dioxide in iron ore, so it is difficult to reduce the coke consumption in blast furnace as iron reduction agent before the new cheap and energy saving reduction agent can take the place of coke. Moreover since the most of production processes are in high temperature, the outputs contain high sensible heat. Recovering and utilizing the waste heat in outputs can efficiently reducing other energy demand within or beyond steel industry boundary.

	Exergy input GJ per tonne crude steel	Exergy output GJ per tonne crude steel	Exergy loss GJ per tonne crude steel	Exergy efficiency	Energy input GJ per tonne steel	Energy output GJ per tonne steel	Energy loss GJ per tonne steel	Energy efficiency
Coke Making	16.96	13.56	3.41	79.95%	16.96	13.56	3.41	79.95%
Crude steel making in integrated steel plant	19.17	12.21	6.96	63.69%	18.6	5.11	13.49	27.47%

Table 22: Compare the energy and exergy consumption for coke making and crude steel production.

Making Crude steel consumes 90% of primary energy in the UK steel industry in 2009 and another large amount energy related to steel industry is consumed for coke making. Comparing the exergy and energy datum in Table 17, 18, 20 and 21, the energy efficiency and exergy efficiency of coke making is higher than that of crude steel making since the coking process is an energy transmission process and most of energy is remained in coke and recovered in by-products. While in all integrated steel plant, besides the coke for reduction agent demand, a large amount of coke is combusted to keep the high temperature inside blast furnace in order to meet the requirement of iron ore reduction reaction, which normally reaches 2000°C.

Comparing the energy inputs and outputs of crude steel production in integrated steel plant, the energy efficiency is very low, because crude steel is not a kind of fuel out- put and it is difficult to be used for energy demand. However, crude steel as the main product contains high chemical exergy 7.1 GJ per tonne steel in steel, which pushes the exergy efficiency much higher than energy efficiency. So, during the complicated iron ore reduction process, some energy is applied to destroy the structure of iron ore and form the structure of iron and same energy is transformed to the chemical exergy in iron. Compare the exergy loss and energy loss for crude steel making in all integrated plant, the energy loss is much more than exergy loss because it is difficult to find out how much energy is used for reduction reaction by comparing energy inputs and outputs. By exergy analysis, the exergy difference between iron ore and crude steel is the theoretical minimum energy demand for reduction reaction. So avoiding reducing the exergy loss is to reduce exergy inputs, increase available outputs and avoid the exergy loss druring irresistible processes, like combustion.

The directly way of reduce the energy consumption in coke oven is to reduce the demand for coke. Quite lots reduction agents can theoretical take the place of coke with low energy demand, like hydrogen, natural gas, heavy oil, however, considering the high cost of these alternative reduction agents, cooking coal is a good choice to partly take the place of coke. Direct coal injection in a blast furnace is an effective technology to reduce the consumption of coke and then saving energy in the coke production [55]. According to the calculation from Hoogovens, the net energy savings are 3.76 GJ per tonne coal injection [55]. In the UK, direct coal injection is adopted by the blast furnaces in Scunthorpe. The result is clearly shown in table 19 that the coke consumption is lower than other blast furnaces. In principle, improving the proportion of coal injection in a blast furnace can save more energy. According to Andrzej's study [75], the direct coal injection needs increasing COG supply as fuel, meanwhile, the directly injected coal also would increase the output of BFG and its LHV, and so the energy consumption is unchanged [75].

In the UK, every iron and steel plant have its own energy consumption levels due to different technical levels as shown in Table 19. In order to give a general energy saving suggestion for modern steel industry, the following Table 23 introduces the main hot flow in steel industry based on a reference steel plant described by the International Iron and Steel Institute (IISB) [50]. Compare current energy consumption for coke making and crude steel making in UK with available energy saving technology, Figure 38 shows the energy saving potential from waste heat recovery in coke making and crude steel making via blast furnace and basic oxygen furnace.

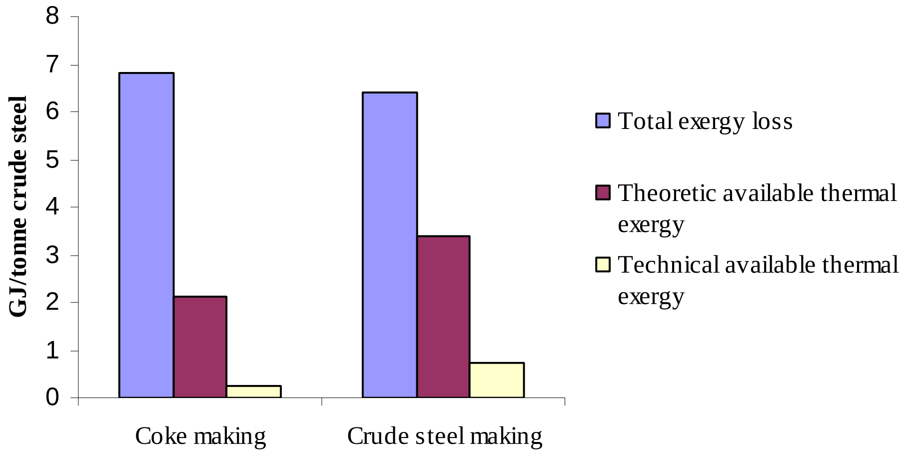


Figure 38: Waste heat recovery potential in coke making and crude making processes

The theoretic exergy in waste heat from coke making and crude steel in integrated plant in UK is 5.49GJ per tonne crude steel. As shown in Figure 33&35, the exergy loss in cooking process and crude steel production in BF-BOF are 28% and 34%. These exergy losses are mainly due to combustion, internal and external heat transfer, chemical reaction and sensible heat loss. In steel industry, waste energy recovery is an important section for reducing energy cost. From coke plants to steel casting plants, all generation processes are operated in high temperature environment due to the properties of steel. During these generation processes, besides the main products, such as coke, sinter, iron, crude steel and finished steel, there are lots of other outputs. Because of the high value of sensible heat in these outputs, these by-products can be used for heat resources. Moreover, the pressure of BFG is quite high and can be used to drive turbine for electricity generation.

Unit operation	Hot flow (gas/solid)	Sensible heat (GJ/trs)	Exergy (GJ/trs)	Maximum temperature (℃)	Technique	Stage of development
Coke making	Hot coke(s)	0.24	0.14	1100	Dry coke quenching,	Commercial
	COG(g)	0.24	0.12	700	Waste heat recovery	Stopped
Sintering	Sinter cooler gas(g)	0.97	0.28	350	Advanced sintering machine or Emission optimized sintering	Commercial
	Sinter exhaust gas(g)	0.23	0.12	350		Demonstration
Blast furnace	BFG(g)	0.82	0.33	500	Top-pressure recovery turbine using dry-cleaning	Commercial
	BF slag(s)	0.39	0.26	1300	Radiant heat boiler	Prototype, R&D stopped since end of 1980s
Basic oxygen furnace	BOF gas(g)	0.19	0.12	1200	BOF gas recovery Combined boiler/suppressed combustion	Commercial Commercial
	BOF slag(s)	0.02	0.01	1500	Radiant heat boiler	Prototype, R&D stopped since end of 1980s
Casting	Cast steel (s)	1.39	1.06	1600	Radiant heat boilers with heat pipes Slab cooler boiler	Commercial Commercial
Hot strip mill	Hot rolled steel(s)	1.04	0.62	900	Water spraying and heat pumps	Commercial
Total		5.53	3.06			

Based on References 29 and 30.GJ/trs, gigajoule per tonne of roll steel

Table 22: Waste heat recovery techniques for process gases and solid flows in an integrated steel plant [50]

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However, the recovery and utilization of waste energy coming from steel generation process are very complicated technologies and technical availability and reliability and commercial availability should be considered. During the processes of the utilization of waste energy, some energy would be sent back into steel generation system, some would be used to generate electricity, and some low temperature heat resource can be used to generate steam for other industrial utilization or used as heat resource to supply heat for other industrial process directly. In an integrated steel plant, major energy products are COG, BFG and BOFG (basic oxygen furnace gas) and the major heat emissions are from hot coke. DCQ (Dry Coke Quenching), TRT (Top Pressure Recovery Turbine) and BF Hot Stove energy recovery are the state-of-the-art technologies utilized in Japanese steel plants [48]. Table 23 shows the technologies currently being utilized in steel industry to recover waste energy. Due to the lack of information about the energy recovery in British steel industry, the energy recovery potential cannot be calculated accurately; however these methods in table 21 can be recommended.

Actually, considering most of working process in iron and steel industry needs heating and high temperature, there is lots of low temperature waste sensible heat in every production stage in this sector. These waste heat are not be recovered because the temperature is too low to be recovered. However, the amount of this low temperature heat is huge in iron and steel industry. If this waste heat can be collected, it should become a good and large heat resource for heat pump working. The iron and steel plant can work as a heat supply center to supply heat to other customer using the recovered low temperature waste heat. This way cannot reduce the energy consumption in iron and steel industry, but it can improve the whole energy utilization efficiency in whole society.

6.5 Summary

After reviewing the state-of-the-art technologies, it is obvious that the iron and steel industry will be continuously acting as an energy-intensive industry in the UK. In addition, with the development of city regeneration progress which currently happens in the UK, the demands of steel will increase in the next couple of years, which would increase the energy demand of the iron and steel industry.

Based on the analysis above, the energy saving potential in the iron and steel industry are in the thermal energy consumption stages and waste heat recovery processes. The results of exergy analysis show that the main exergy losses in an integrated steel mill are due to the requirement of high temperatures. So reducing the heat demand for intermediate reheating, reducing the temperature difference in every process step, and recovering waste and utilizing the heat from high temperature processes are three major research directions for long-term energy-efficiency improvement in iron and steel industry.

7. Carbon emissions in the iron and steel industry and new technologies review

7.1 Carbon emissions factors and carbon emission calculation in British iron and steel industry

According to the Intergovernmental Panel on Climate Change (IPCC), 3-4% of world CO_2 emission is from the iron and steel industry. A similar situation happens in the UK. Due to the relationship between energy and CO_2 emission, energy analysis in industrial processes can not only find most energy saving potentials but also point out the effective ways to reduce carbon impact.

CO_2 emission from different energy resource can be calculated according to the CO_2 emission factors of the energy resources. The CO_2 emission factor is the quantity of CO_2 emission per energy consumption unit. For fossil fuel, the CO_2 emission is determined by the carbon content of the fuel. For electricity, the factor is a calculated average value, which is the ratio of the carbon emission from all power plants supplying electricity to the grid and all electricity supplied to the grid from these power plants in a nearest certain period, normally the whole last year. For renewable energy, like wind power, it does not emit CO_2. Table 23 & 24 are the main energy CO_2 emission factors in the UK. And the CO_2 emission factors of natural gas and electricity in the UK are 58.3 tCO_2/TJ [78] and 0.537 kg CO_2/kWh [61].

	CO_2 emission factor [t CO_2/TJ]																		
	Primary fuels			Second fuels/Products															
	Crude oil	Orimulsion	Natural Gas Liquid	Gasoline	Jet Kerosene	Other Kerosene	Shale Oil	Gas / Diesel Oil	Residual Fuel Oil	LPG	Ethane	Naphtha	Bitumen	Lubricants	Petroleum Coke	Refinery Feed stocks	Refinery Gas	Other Oil	source
IPCC default	**73.3**	**80.1**	**63.1**	**69.3**	**71.5**	**71.9**	**73.3**	**74.1**	**77.4**	**63.1**	**61.6**	**73.3**	**80.7**	**73.3**	**100.8**	**73.3**	**66.7**	**73.3**	
UK	IPCC	78.4	IPCC	70.9	72.5	72.5		73.6	76.7	65.0	IPCC	IPCC	IPCC	IPCC	79.8	IPCC		IPCC	CRF2003

Table23. Comparison of IPCC default CO_2 emission factors and UK specific factors for liquid fuels [t CO_2/TJ, basis NCV] [62]

	CO_2 emission factor [t CO_2/TJ]											source
	Primary fuels							Second fuels/Products				
	Anthracite	Coking Coal	Other Bit. Coal	Sub-bit. Coal	Lignite	Oil Shale	Peat	BKB &Patent Fuel	Coke Oven Coke	Coke oven gas	Blast furnace gas	
IPCC default	98.3	94.6	94.6	96.1	101.2	106.7	106.0	94.6	108.2	47.7	242.0	
UK	98.7	89.6	IPCC					111.6	106.2			CRF2003

Table24. Comparison of IPCC default CO_2 emission factors and UK specific factors for solid fuels [t CO_2/TJ, basis NCV] [62]

With the help of CO_2 emission factors, the carbon emission from energy consumption can be calculated as follows [68]:

$$C_j = E_j \times F_j \tag{21}$$

Here C_j is the carbon emission from energy j consumption; E_j is the quantity of energy j consumption and F_j is the specific CO_2 emission factor of energy j. So the total CO_2 emission of an industry sub-sector can be got as follows [68]:

$$\Sigma C_j = \Sigma (E_j \times F_j) \tag{22}$$

According to DUKES 2011 [77], the total energy consumption by British iron and steel sub-sectors in 2010 is 108.27×10^3 TJ and total CO2 emission is 11.26 Mt CO2, including coke manufacturing From Figure 39, it is clear shown that electricity has become the largest energy input and contributes near 49% CO_2 emission of the iron and steel sub-sectors in UK. Natural gas contributed the second large energy consumption and as well as second large CO_2 emission

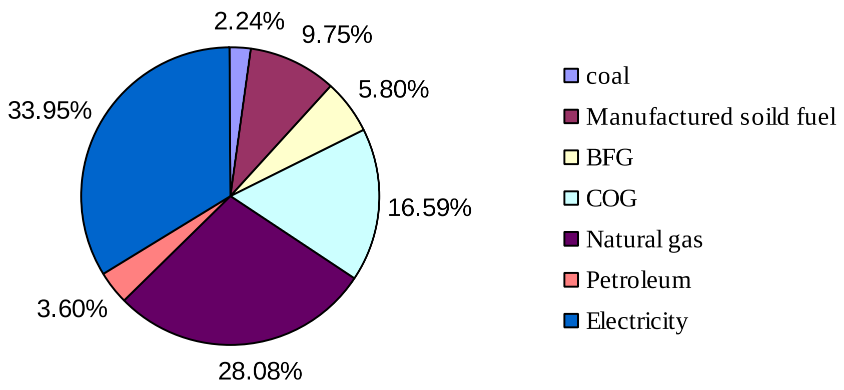

Figure 39: Shares of energy consumption in iron and steel sector in UK 2010, including coking industry (Source: [70])

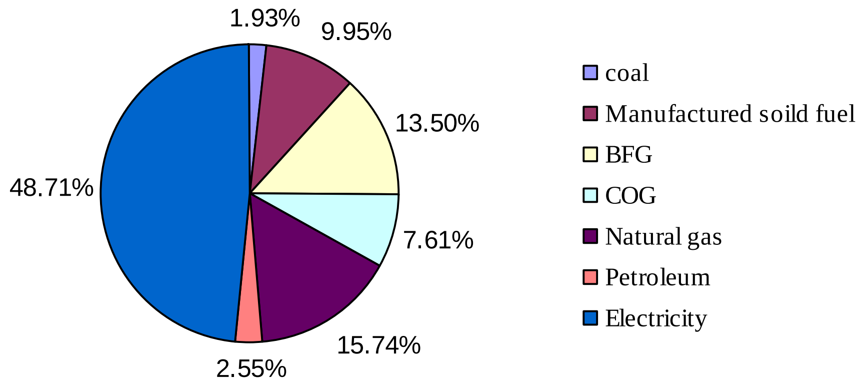

Figure 40: Shares of CO_2 contribution in iron and steel sector in UK 2010, including coking industry (Source: [70])

7.2 Carbon emission reduction potential in the UK iron and steel industry

In blast furnaces, coke not only supplies heat to keep the high temperature reaction environment but also acts as a reduction agent to reduce iron from ore. As the production of the chemical reaction between iron ore and coke, CO_2 is another main product besides pig iron. Considering the relationship of the reaction products as shown in chapter 6.3.3, if carbon is used as a reduction agent, neither in form of coke nor in form of coal, the final reaction products ration in theory should be as shown as following formulae, ignoring the actual mid-reactions and their products, like CO.

$2Fe_2O_3 + 3C = 4Fe + 3CO_2$

$Fe_3O_4 + 2C = Fe + 2CO_2$

Therefore, there are two effective ways to reduce CO_2 emission from conventional coke-fired blast furnace. The first one is developing new reduction agents with less CO_2 emission ratio or without CO_2 emission, and the second way is reducing the demand of pig iron, which means developing more EAF plants to take the place of conventional integrated steel plant. So the share of EAF plants has become an important index to indicate the CO_2 emission level of iron and steel industry in a country. Table 23 illustrates the possible potentials of reducing CO_2 emission by improving the share of EAF in the whole iron and steel industry among those countries.

	Steel production (Mton)		Share of EAF (%)		Ration of iron/crude steel (%)		Share of cold rolled (%)	
	1986	**1994**	**1986**	**1994**	**1986**	**1994**	**1986**	**1994**
Korea	14.6	33.7	35	36	0.62	0.63	28	36
Mexico	7.2	10.3	40	63	0.52	0.34	20	14
Brazil	21.2	25.7	24	21	0.95	0.98	24	27
China	52.2	92.6	20	21	0.97	1.05	6	6
India	12.2	19.3	26	26	0.86	0.92	10	17
US	74.0	91.2	37	39	0.54	0.60	35	40
UK	14.7	17.3	27	25	0.66	0.69	N/A	22

Table 26: Crude steel production and shares of the main production processes in 1986 and 1994 [60, 64]

Increasing the share of the steel from EAF plants can reduce the demand of coke directly and then brings a series changes in the industrial chain of steel industry. The CO_2 emission due to the transportation of iron ore and coking coal can be reduced and the CO_2 emission from coking plant also can be reduced due to the decreasing of coke demand, which is a dramatically CO_2 emission resource outside the boundary of iron and steel. However, due to the high electricity demand of EAF plants, the CO_2 emission issue actually becomes a problem about reducing electricity consumption and reducing the carbon f actors of the grid.

However, in fact the steel from EAF plants currently cannot meet the market demands and actually steel from integrated steel plants still occupies most of the steel market, not only in the UK but also in the world.

Steel production from iron ore is a series of complicated chemical and physical processes with lots of by-products. By analyzing the steel produce process from raw materials, like coke, iron ore, to crude steel, most of primary energy is consumed in blast furnaces where also generate most of the GHGs in whole steel industry, such as CO_2 and CH_4. So the main energy saving and CO_2 emission reduction potential comes from the blast furnace. As discussed in chapter 6.3.3, the main energy input of a blast furnace is coke, which supplies 76.8% of energy in the blast furnace to keep the blast furnace running at 1400 ℃. Actually, there is only 61% of all coke input being used for heat demand; another 39% of the coke input works as reduction agent to react with iron ore. But both of the coke utilizations would produce CO_2 emission finally. Considering the high carbon content in coke, it is very clear that reducing CO_2 emission from blast furnaces is a technical problem of reducing the use of coke in blast furnaces. Because coke is the energy resource and reduction agent in blast furnaces, reducing coke consumption means reducing the energy demand of blast furnaces and using a new low carbon reduction agent to replace coke.

7.3 Available technologies for carbon emission reduction

As it is discussed above, coke is the main energy supplier to meet the requirement of high temperature that is necessary for the chemical reaction of iron production in blast furnaces, so using less energy to meet the requirement of reaction is an efficient measure of reducing coke consumption. Currently the most efficient and economic available way is improving the temperature of the raw materials, which are normally preheated by the waste heat collecting from some high temperature operation processes.

Because of the high temperature in blast furnaces, all products, by-products and waste from blast furnaces contain high value thermal energy. Collecting these waste heats and using them inside or outside steel industry can reduce extra energy consumption to reach the target of CO_2 emission reduction. Actually, there are two forms of energy contained in blast furnace (BF) gas, thermal energy due to high temperature and high top gas pressure and chemical energy of the CO and CH_4 in BF gas. So energy recovery from BF gas is widely used for power generation with TRT (Top gas pressure Recovery Turbine) technology and CCPP (Combined Cycle Power Plant) technology in modern steel industry. CCPP technology can utilize not only BF gas but also some low heat value gas, like BOF (basic oxygen furnace) gas for power generation. So CCPP can recover energy from most gaseous products in an integrated steel plant with high efficiency. TRT and CCPP can reduce the demand of purchased electricity; and then reduce the line loss of grid.

If the electricity generated from TRT and CCPP is supplied to grid, it also can decrease the carbon emission factor of the grid because both of these power generation technologies are green power generation technologies with lower CO_2 emission than coal-fired power plants.

Therefore, preheating technology with recovered waste heat can reduce energy demand inside iron and steel industry boundary, while TRT and CCPP technologies can extend CO_2 emission reduction outside iron and steel industry boundary.

Meanwhile, coke in blast furnace is not only used as energy, but also for the need of a reduction agent. So, developing new high efficiency reduction agents with low energy demand and low carbon emission can effectively reduce CO_2 emission .Currently, natural gas, oil, plastics and animal fat are all tested as reduction agents in some plants and the result of CO_2 emission reduction is dramatically, for example, 1 GJ coke leads to an emission of CO2 of about 103 kg while 1 GJ natural gas emits about 56.5 and animal fat 0 kg CO_2 [65]. In addition, the technology of reducing iron by hydrogen has been developed [65], which only produces water (H_2O) as the final product of reaction and can achieves the target of zero carbon emission during iron production in blast furnaces.

However, each of these materials has not met the requirements of commercial utilization due to their special reasons. For example, hydrogen and natural gas are both good choices, but it is an energy-intensive process to produce hydrogen based on current industrial technology and for natural gas, high price makes the high cost problem.

In today's leading steel plants, PCI (Pulverised Coal Injection) technology has become a state-of–art technology with a series of advantages. Pulverised coal is used as fuel to replace part of coke. During the process of pulverised coal combustion in blast furnaces, more CH_4 and hydrogen would be released than coke combustion and these contents are very good reduction agents to improve pig iron quality and also increase the heat value of BF gas, which can improve BF gas quality to produce more electricity in CCPP power plant. Moreover, PCI technology directly reduces the consumption of coke and also reduces the production of coke from coke plants, which is a heavy pollution and high energy-intensive industry. Actually, the ration of PCI coal consumption and hot metal production from blast furnaces has been an important index to evaluate the energy consumption and CO_2 emission of a steel plant, a steel company or iron and steel industry in a country. Based on the Best Available Technology (BAT) in iron and steel industry recommended by the EU IPPC report [66], the consumption of coke and coal for producing one tonne hot metal is 270-300 kg coke and 210 kg PCI and the ration of PCI coal and coke is about 0.7-0.78 kg PCI coal/kg coke, which means that BAT can use PCI coal share about 41%-44% of total fuel and reduction agent input in blast furnaces. In the UK, PCI technology has been widely used from 1990, and the British Streel has the leading PCI technology in the world. In 1999, the British Steel has succeeded in increasing PCI to 300g/tHM in some of its iron plant, and now it is testing to improve PCI consumption to 50% of fuel input in blast furnaces. Comparing with BAT, the ration of PCI and coke consumption of whole British iron and steel industry is about 0.21 and there is still a big difference with the ration 0.78 based on BAT (see Figure 43). However, PCI would decrease the temperature in blast furnace.

In order to avoid the temperature drop in blast furnaces, high temperature and oxygen enrichment blast technology is applied for temperature compensation due to PCI application. Increasing blast temperature can increase the temperature in blast furnaces and higher working temperature in blast furnaces can reduce the demand of coke because of higher combustion efficiency. The reduction of the use of coke as a reduction agent would decrease CO_2 emissions directly. If the blast temperature is increased by about 100°C, the coke consumption as reduction agents would decrease 10 kg/tHM [65] and the reduction of 10 kg coke/tHM would reduce CO_2 emissions by about 29 kg/tHM [65]. Higher blast temperature can be obtained by increasing the content of energetic coke oven gas (COG) in the gas mix heating the hot stoves, which does not need any extra investment since the additional COG is redistributed from the slab furnace [65]. Therefore, optimizing blast temperature and improving PCI is the BAT to reduce CO_2 emissions from iron production process.

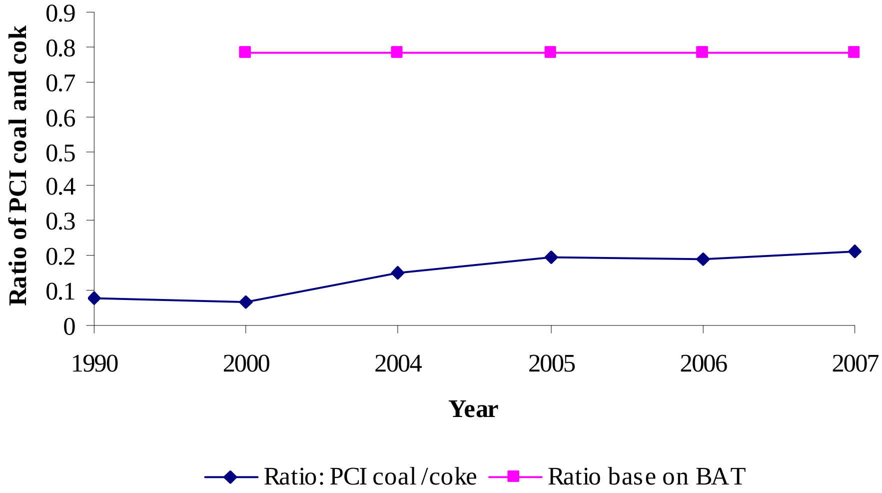

Figure 43: Ratio of PCI coal and coke consumed in UK iron and steel industry

7.4 Carbon capture and storage (CCS) technology

Since coke and coal are still main fuel input in most of blast furnaces in the UK. So it is impossible to produce pig iron from blast furnace without CO_2 emissions. Preventing the CO_2 emissions from blast furnaces from emitting into global atmosphere system is a new idea of reducing CO_2 emissions from iron and steel industry. Carbon capture and storage (CCS) technology is being developed according to this thought and has been used in conventional coal-fired power generation industry to reduce the CO_2 emissions in off-gas of the boilers.

In iron and steel industry, especially iron production process in blast furnaces, is obviously a large CO_2 emissions resource. The BFG contains 2% hydrogen, 25% CO， 15% CO_2, 58% N_2 and a few of other contents. The LHV of BF gas is about 3300KJ/Nm^3. The concentration of both CO2 and CO is about 40%. The technology of removal CO_2 emissions from high temperature and high pressure blast furnace gas with complicated content is difficult and expensive. So CCS technology is still in the study stages without large scale application due to the high cost.

The latest research from Japan gives some good news about the application of CCS in iron and steel industry [67]. They clean the BF gas and then compress it to 20 bar [67] in order to improve CO_2 capture efficiency. The high temperature clean BF gas would react with high temperature steam, about 400°C, to convert CO into CO_2 and H_2. Then most of the carbon would be in the form of CO_2 with high concentration [67]. These CO_2 would be captured by Selexol and then about 85–99.5% of the CO2 would be removed from the gas [67]. The residual gas contains nearly 30% H_2 and high heat value and can be used in IGCC power plant. The captured CO_2 would be compressed to 100 bar for transportation and storage like all other CCS system applied in other industries. There are three main energy-intensive processes, compressing BF gas to 20 bar, producing high temperature steam for reaction and compressing CO_2 for transportation and storage. The hot steam can be produced by using waste heat from iron or coke production processes and then CO_2 would be compressed to 100 bar for transportation and storage in depleted oil and gas fields, saline aquifers or in the ocean, which is the same energy consumption as CCS used in other industry. So the only the special energy consumption process is compressing BF gas to 20 in the BF gas CCS system.

The Japanese research shows that the cost of CCS application in iron industry can be reduced to 10.3-18.8 US$/t CO_2, which is similar to the cost of CCS application in a new coal-fired power plant [67], so that should be attractive and cost acceptable to iron and steel industry.

7.5 Summary

Iron and steel industry is the most important research target of CO_2 emissions reduction, from policy study to technology development, since it involves the high energy consumption and high coke consumption as reduction agent for iron production. In the analysis above, iron production in blast furnace is the main CO2 emissions resource. PCI application, improving PCI ratio and developing new, low carbon and low cost reduction agent are the most effective ways to reduce CO2 emission produced from blast furnaces and CCS technology can prevent the carbon in BF gas from emitting to environment. So blast furnaces are the main CO2 emission resource in UK iron and steel industry and are also the biggest CO2 emission reduction potential.

From the scale of the whole iron and steel industry structure in the UK, reducing the demand of iron and improving recycling steel production from EAF with more clean and low carbon electricity supply is the most effective way to reduce CO2 emissions in a large scale, which needs a structure change of UK steel industry.

In addition, those energy saving technologies, like waste heat recovery from all stages of iron and steel product production process, also should be widely applied because any small progress of energy saving technology in iron and steel industry can save a lot of energy in quantity and reduce a large amount of CO2 emissions because of the energy saving.

8. Conclusion and future work

8.1 Conclusion

Energy shortage and the climate change in the 21^{st} century has become the footprint of industrialization. Ways of limiting resources to support the sustainable development of the world without destroying the fragile environment and ecological system are challenging the humanity's capacity to change. The relationship between fossil fuel combustion and CO_2 make energy saving technologies the mainstay of carbon emission control. The Kyoto Protocol requires greenhouse gases emission reductions (and also change in energy policy) in every country, especially in the industrialized countries.

Exergy analysis is widely used for the study of energy consuming processes, especially thermal processes, together with the energy analysis base on the First Law of Thermodynamics. Exergy analysis shows the nature of energy consuming, and can point to the main exergy losses. By the exergy analysis in the sugar and iron and steel industries, a number of options have been indentified: avoiding low temperature combustion, reducing high temperature difference in heat transfer processes and recovering the waste heat from high temperature processes. Such energy saving technologies may be used in many energy intensive industrial sub-sectors. Energy multipurpose use is a concept based on exergy analysis. According to the present results, it may be used to find the requirement for energy quality in each energy process, and then arrange the energy flow through each process such that exergy losses are minimized. The energy system distributes and supplies energy to a certain area or system. Therefore, energy multi-purpose use may be an effective energy quality management method.

Iron and steel industry is a traditional energy-intensive industry. The exergy analysis in this sub-sector can be used as an example to direct the energy saving research in other high temperature industries. According to the exergy analysis results, the traditional route is modifying the production processes in iron and steel industry to order to improve energy efficiency. New iron and steel making technologies to avoid some intermediate reheating and new waste heat recovery technologies. Considering the target of iron and steel industry, another route to reducing energy consumption and CO_2 emission is via the development of new materials that has the same characters as steel and can take the place of steel in some fields in order to reduce the demand of steel. In the iron and steel sector, the first route is to reduce the energy consumption from the iron and steel making side, and then to encourage energy saving by the steel end-users. Increasing the recycling of steel from Electric Arc Furnace and adopting more non-steel materials to replace steel would be the most useful and direct methods in current stage to reduce the energy consumption and carbon emissions associated with in iron and steel industry in the UK.

8.2 Future work

In this research, the relationship between fossil fuel combustion and carbon emission reduction and the relevant calculation have been introduced. The method of CCS can be used widely in heavy carbon emission industries. However, the thermal power plant is only the start stage of the power sector. The electricity supply system, including power plants, the transmission and distribution grid, and electricity customers, acts as the bridge between energy resources and energy end-users. Improving the efficiency of electricity supply system should include not only the efficiency of power generation, but also the efficiency of electricity transmission and distribution system. In electricity transmission and distribution system, electricity transmission voltage decides the losses. For the requirements of reducing loss, electricity transmission line normally runs at high voltage for long distance power supply. Transformers change the voltage to the level that electricity user need, so reducing the loss made by transformer is an important aspect of energy saving in electricity transmission and distribution system. There is a large energy saving potential by using new type of transformer with high efficient technologies. For example, energy saving transformers can save 100-150 TWh/year of electricity in OECD countries, equivalent to more than 70 million tonnes of CO2 emissions [68].

In industrialized countries, the power transmission and distribution system is complicated. Besides economic character, safety, reliability and other factors should be considered. In the future research, the whole electricity system in the UK would need to be researched from power generation to electricity user. The research work in the next stage should focus on the analysis of British grid system and power generation structure in order to find the emission factor for an electricity system [68], which can help establish the relationship between electricity end-user and carbon emission. Decarburization of the power sector can be used to direct the energy policy making and electricity system promotion.

However, all new technologies only make it possible to improve energy and exergy efficiencies in industrial sector. The cost rise by adopting new low or zero carbon technologies would become a main barrier. Legislation and low costs technologies would become the two main drivers to push the industrial sector development to the low or zero carbon direction [new]. The firms emitting more pollution should be punished seriously that would cost them more than investing new ‘clean’ technology. Emissions trade is a new way to manage energy and emission in industrial sector. On a European scale, the EU Emissions Trading Scheme (EU ETS) is a ‘cap and trade’ policy, which aims to create a market for carbon. Phase I runs from 2005 to 2007, with the commencement of Phase II in 2008 until 2012 [new]**,** and London had become the main carbon trade market. However, the uncertainty of the carbon policy for future makes the wave of the carbon price in market, which would affect the activity of the firms on low or zero carbon technologies. So saving energy and reducing GHG emissions are not only a technical problem, but also a political issue.

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